Radiative Forcing of Southern African Climate Variability and Change

Report to the
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by

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Executive Summary

This report is concerned with exploring the effects of various forms of tropospheric and stratospheric radiative forcing (e.g. Antarctic stratospheric ozone, increasing CO_2 concentrations and time-varying aerosol forcings) on southern African climate variability and change. A large set of sensitivity tests, following the experimental design of the Atmospheric Model Intercomparison Project (AMIP) was performed for this purpose. An ensemble of projections of future climate change has also been analysed, to investigate the relative importance of enhanced CO_2 concentrations and recovering stratospheric ozone in forcing southern African climate during the 21st century.

The simulations of seasonal circulation anomalies are in general most skilful for the austral summer. This result provides some insight in the relatively high levels of skill reported in general for the prediction of summer rainfall totals over southern Africa at the seasonal time-scale – this skill stems from the underlying circulation fields being forecasted skilfully for summer. The drastic reduction in skill that occurs in the autumn, winter and spring seasons over southern Africa (as demonstrated in this report) may be attributed at least partially to the seasonal northward-displaced westerlies, with its associated transient weather systems of which the variability is simulated less skilfully. Another important contributing factor may be that ENSO related SST anomalies are generally the largest during the early summer, with important regional SST anomalies such as those associated with the South Indian Ocean subtropical dipole being the largest in the late summer. That is, the abilities of the tropical Pacific Ocean and regional oceans to force climate variability over southern Africa are reduced outside the austral summer. These arguments suggest that improvements in forecast skill may be extremely difficult to attain for the seasons of autumn, winter and spring.

The inclusion of time-varying stratospheric ozone concentrations improves the simulation skill of circulation variability over the Southern Ocean in spring and over southern Africa in summer. This result is consistent with dynamic circulation theory, according to which stratospheric forcing over Antarctica in spring has a pronounced mid-latitude response in summer. However, this study is the first to demonstrate that this response actually reaches the subtropical latitudes of southern Africa. The inclusion of time-varying CO_2 concentrations offer some benefit for the simulation of summer-time inter-annual variability, particularly in the tropics. The simulated changes in skill are, however, negative for most other seasons and regions. The prognostic treatment of aerosols is problematic in the model simulations for winter, and leads to decreases simulation skill over the southern African interior. However, the use of prognostic aerosols improves the model to simulate inter-annual variability in spring and summer circulation, for most of the southern African region.

The analysis of simulated temperature trends for the various radiative forcing simulations has yielded an important result – the inclusion of time varying CO_2 concentrations is essential to realistically simulate the observed trends, even in the presence of observed SST forcing. This result suggests that the local increased absorption of infra-red radiation through enhanced levels of CO_2 plays an important role in the strong temperature trends observed over southern Africa. Under low mitigation, and even under relatively high mitigation scenarios such as RCP4.5, the poleward displacement of the westerlies is projected to strengthen during the 21st century – despite the recovery of stratospheric ozone concentrations. This large-scale hemispheric change in the circulation is contributing to the projected changes of rapidly rising surface temperatures over southern Africa in winter, and the robust projections of decreasing rainfall over the southwestern Cape. The maintained poleward displacement of the westerlies may also contribute to the occurrence of increased rainfall totals projected by some climate models over eastern South Africa, particularly during summer.

The CCAM simulations forced with time-varying ozone concentrations are able to reproduce the most important dynamic and thermodynamic features of the stratosphere and the troposphere. The most important shortcoming in the simulations is the colder South Pole (compared to observations) and a persistent relatively weak meridional temperature gradient in the stratosphere, particularly for

the summer months. This systematic error prevents the full reversal of the stratospheric flow to occur. This might have implications for the simulation of stratosphere-troposphere coupling. The tropospheric circulation is simulated realistically in general. Forcing CCAM with time-varying ozone fields enables the model to successfully simulate the impact of ozone depletion. All the well-known results from studies that have been conducted with chemistry-climate models with interactive stratospheric chemistry are reproduced here, including the pronounced southern displacement of the westerlies in summer under depleted stratospheric ozone. Momentum fluxes demonstrate the impact that ozone depletion may have had on weather systems affecting South Africa. It appears to have shifted some of the weather systems eastward and southward, with enhanced easterly flow over South Africa in summer. This may have contributed to the increasing trends in rainfall observed over parts of the summer rainfall region of South Africa, particularly in summer.

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Chapter 1
Introduction

The climate of the southern African region is highly variable, and prone to the occurrence of both droughts and floods (Dyer and Tyson, 1977; Jury et al., 1993; Reason and Rouault, 2002; Rouault and Richard, 2003; Singleton and Reason, 2007; Malherbe et al., 2012). The interaction between natural causes of this variability, and a potentially increasing human influence, is not fully understood (Joubert et al., 1996; Fauchereau et al., 2003; Engelbrecht et al., 2013; Winsemius et al., 2013). There are three main types of atmospheric radiative forcing that are known to have the potential to significantly impact on global climate variability and change. These are the enhanced (anthropogenic) greenhouse effect, the depletion of the ozone layer in the polar stratosphere and sporadic changes in the concentration of aerosols (including sulphur dioxide in the stratosphere). Over the past five decades, the climate has warmed globally and over much of the Southern Hemisphere (Jones et al., 2012). Overwhelming evidence exists to attribute this warming to the enhanced greenhouse effect (IPCC, 2013). Due to its location in the subtropics, the southern African landmass is particularly vulnerable to the regional effects of global warming. Temperatures over the central interior regions of southern Africa have been rising at about twice the global rate of temperature increase over the last five decades (Kruger and Shongwe, 2004; Engelbrecht, 2010; Jones et al., 2012; Engelbrecht et al., 2015) and are projected to continue to rise this relatively high rate over the coming century (e.g. Christensen et al., 2007; Engelbrecht and Bopape, 2011; James and Washington, 2013; Engelbrecht et al., 2015). Moreover, there is evidence that systematic changes in the larger-scale Southern Hemisphere circulation have taken place in recent decades. The circumpolar westerly winds have increased in strength, and have shifted southwards (e.g. Thompson and Solomon, 2002; Son et al., 2008). This has occurred in association with an increase in the height of the tropopause, particularly in the polar regions (Son et al. 2010), and an expansion of the Hadley cell (Hu and Fu, 2007; Son et al. 2010). The changes in the circumpolar westerlies have exhibited the largest amplitude in spring and in summer, and are thought to be to a large extent caused by ozone depletion in the stratosphere above Antarctica in spring (e.g. Gillett and Thompson, 2003). This effect is being strengthened through the enhanced greenhouse effect (e.g. Cai and Cowan, 2007), since carbon dioxide has cooled the lower stratosphere (Held, 1993). Finally, sulphur dioxide induced radiative forcing is known to sporadically disrupt climate patterns, during periods of enhanced volcanic activity that lead to high concentrations of sulphur dioxide in the stratosphere. By reflecting large quantities of sunlight back to space, enhanced concentrations of sulphur dioxide may induce periods of global cooling – a recent example is the cooling period that followed the eruption of mount Pinatubo in 1991 (e.g. Minnis et al., 1993).

Although the larger-scale forcing effects of the three main types of radiative forcing are to some extend understood, their interactions to cause climate variability and change over the southern African region remain largely unexplored. For example, there is evidence to suggest that in summers preceded by strong cooling of the Antarctic stratosphere in spring, the strengthening of the circumpolar westerlies occur in association with a strengthening of the easterlies at about 30 S (Gillett and Thompson, 2003). There is the potential for such a large-scale change to impact significantly on southern African summer rainfall patterns, also taking into account that ozone depletion has recently been linked to changes in subtropical rainfall patterns (Kang et al. 2011, Feldstein, 2011). Demonstrating an impact of anthropogenically-induced ozone depletion (in combination with natural variability as induced by the polar vortex) on southern African rainfall patterns may hold benefits for improving the skill of seasonal weather forecasting over the region. At the climate change time-scale, it is important to understand how the expected recovery of the ozone hole (that is, of stratospheric ozone concentrations above the poles) will interact with increasing greenhouse gas concentrations to impact on Southern Hemisphere and southern African regional climate change (e.g. Cai and Cowan, 2007). At the climate-change time scale the enhanced greenhouse effect is the primary forcing mechanism applied within the global circulation models (GCMs) used to make projections of future climate change. However, at the seasonal time-scale the potential benefits of initializing and forcing GCMs with updated greenhouse gas concentrations (rather than climatological averages of these values) remain to be explored. Finally, periods of enhanced stratospheric sulphur dioxide concentrations is an important natural radiative forcing mechanism, that may interact with the anthropogenically induced sources of ozone depletion and the enhanced greenhouse effect. In particular, periods of anomalous sulphur dioxide concentrations may induce El Niño-Southern Oscillation (ENSO) events in the Pacific Ocean (e.g. McGregor and Timmerman, 2011), thereby impacting on southern African climate variability and rainfall patterns.

This report is the first study that investigates how the three main types of atmospheric radiative forcing interact to influence southern African climate variability and change. Within the context of present-day climate variability and seasonal forecasting, the potential incorporation of the effects of depleted ozone concentrations and enhanced greenhouse gas concentrations as additional forcing mechanisms models has the potential to improve forecast skill. Such improvements will hold benefits for water reservoir management and agricultural planning. Similarly, at the climate-change time scale, the effects of stronger circumpolar westerlies, and stronger easterlies in the subtropics (that result from the atmospheric radiative forcings described), have the potential to significantly impact on southern African climate. Of particular importance, is a potentially significant decrease in winter rainfall totals as a result of the southern displacement of the westerly wind regime (thought to be largely driven by the enhanced greenhouse effect) (Christensen et al., 2007; Engelbrecht et al., 2009), and a potential increase in summer rainfall due to the strengthening of the easterlies (possibly in response to stratospheric ozone depletion) (Kang et al., 2011; Feldstein et al., 2011). These potential controls on southern African climate, and how they will evolve (weaken or strengthen) as a function of time (as the hole in the ozone layer recovers and the greenhouse effect strengthens) require rigorous investigation.

As mentioned above there is the potential for the skill of seasonal forecasts over southern Africa to be improved through the incorporation of various types of radiative forcing. Seasonal forecast performance in general is relatively low compared with short-range weather forecasting. For example, spring season rainfall totals are not predicted with high confidence (Landman et al., 2005) owing to the fact that this season is mostly influenced by transient weather systems. Albeit still modest, forecast skill has been demonstrated for the mid-summer when the tropical atmosphere starts to dominate the atmospheric circulation over southern Africa (e.g. Mason et al., 1996, Landman and Mason, 1999). Some potentially useful prediction skill is also found during austral autumn (Landman et al., 2005). Given the status quo, even marginal improvements in seasonal forecast skill can prove to be useful. Seasonal forecasts can improve by a more realistic representation of inter-annual variability, and when trends in the climate are better captured by models (Doblas-Reyes et al., 2006). Natural forcing such as the ENSO phenomenon and the occasional massive volcanic eruption, are significantly responsible for the observed seasonal-to-inter-annual variations in rainfall and temperatures (Joseph and Zeng, 2011; McGregor and Timmerman, 2011), but do not adequately describe most of the significant long-term temperature trends observed globally and also locally. Strong anthropogenically forced warming trends have been observed over southern Africa (Kruger and Shongwe, 2004; Engelbrecht, 2010; Jones et al., 2012; Engelbrecht et al., 2015) and are projected to continue to rise at a relatively high rate (Engelbrecht and Bopape, 2011; James and Washington, 2013; Engelbrecht et al., 2015), consequently justifying the investigation into how the annual update of greenhouse gas (GHG) concentrations in a global model may improve the skill in simulating inter-annual variability over the region. Two objectives of this work is to determine if GHG-forced climate simulations can capture the observed temperature trends over the region, and to establish if there is an improvement in the modelled inter-annual variation of the regional climate system. The skill in simulating summer rainfall variability may also be potentially improved by a better representation of stratospheric radiative forcing and associated dynamics. Idealised modelling experiments (e.g. Kushner and Polvani, 2004) have shown that there is about a 100 day delay between lower stratospheric thermal perturbations and the tropospheric response. The former occurs first with the latter characterised mainly by the poleward shift of the eddy driven jet, as noted above. It is well known that South African summer is associated with variations of the position of the midlatitude westerlies, associated changes in the easterlies, and corresponding storm tracks (e.g. Tennant and Reason, 2005). Because of this dynamical coupling between the stratosphere and troposphere, it is plausible that the variability of the strength and breakup of the stratospheric polar vortex as well as the associated seasonal lower stratospheric ozone variations might have a profound influence on summer rainfall over the southern African region (Kang et al., 2011; Feldstein, 2011).

There are many outstanding theoretical issues in our understanding of the dynamical coupling between the stratosphere and the troposphere. Nonetheless, several studies (e.g. Simpson et al. 2010) have shown that the movement of the jet due to lower stratospheric thermal perturbations has an effect on the propagation of wave activity, and thus on the baroclinic eddies themselves. Classical theory (e.g. Thorncroft et al., 1993) shows that the development of baroclinic waves begins in the mid-latitudes due to baroclinic instability. The associated wave activity, which is dominated by poleward heat fluxes in the early stages of baroclinic development, propagates vertically upward and then horizontally toward the equator and to a lesser extent, poleward, once it reaches the upper troposphere as the baroclinic wave is growing. This growth is made possible by the baroclinic conversion of eddy available potential energy to eddy kinetic energy. On the equatorward side of the jet, which is more relevant for southern Africa, the wave activity is then absorbed in the subtropics by the mean flow (Randel and Held, 1991), thus affecting the subtropical wind flow by means of wave-mean flow interaction mechanisms. These dynamics can be understood both from the view point of a zonally symmetric model of the atmosphere as in Andrews et al. (1987) or from a low frequency basic state flow perspective (Hoskins et al., 1983, Riviere and Orlanski, 2007). The absorption of wave activity is associated with nonlinear anticyclonic wave breaking (Held and Hoskins, 1985, Thorncroft et al., 1993). Therefore, breaking waves in the upper troposphere together with wave activity diagnostics may provide a dynamical link between the movement of the jet and moisture flux divergence in the subtropical regions. A recent study (Ndarana et al., 2011) suggested that the observed increasing (decreasing) wave breaking trends on the equatorward (poleward) side of the jet are caused by ozone depletion. Because of the influence of breaking waves on the flow, this process might have played a role in the observed rainfall trends over South Africa (e.g. Kruger, 2006). It is possible that the expected equatorward shift to be caused by ozone recovery might influence the breaking waves and hence rainfall. Furthermore, southern African rainfall is associated with the Lorenz energy cycle (Tennant and Reason, 2005). In addition to model simulations of climate variability and change under radiative forcing, this report examines the dynamic circulation aspects of the forcing of subtropical southern African climate by Antarctic ozone depletion. In this way, the dynamical and physical basis of the impact of ozone recovery and depletion vs enhanced greenhouse gases in South African climate change is further explored, thereby strengthening the physical basis for providing plausible predictions and projections of climate variability and change over southern Africa.

Against the background of the potential impacts of radiative forcing on southern African climate variability and change as described above, this report aims to quantify these impacts through the use of sensitivity tests performed using GCM. The impact of the inclusion of realistically varying concentrations of GHGs, stratospheric ozone and aerosols (including stratospheric sulphur dioxide) in a GCM on its skill in simulating inter-annual variability is investigated in particular. A separate analysis is performed for each of the seasons summer, autumn, winter and spring. Atmospheric modelling is also performed to investigate how ozone recovery and increased greenhouse gas concentrations will interact over the coming century to cause climate change over southern Africa. Finally, the project aims to improve our understanding of the circulation dynamics by which the effects of stratospheric cooling are communicated to the subtropics, and southern Africa in particular. The report is organised as follows: Chapter two describes and analyses the large set of radiative-forcing experiments that were performed over southern Africa. These simulations explore the relative roles of various types of radiative forcing in driving inter-annual climate variability over southern Africa. In Chapter 3, the relative roles of increasing greenhouse gas concentrations and recovering stratospheric ozone concentrations in forcing southern African climate change during the 21st century is explored. The underlying circulation dynamics of the stratospheric forcing of climate variability and change in the Southern Hemisphere is presented in Chapter 4. Conclusions are drawn in Chapter 5.

Chapter 2
Simulations of the radiative forcing of southern African inter-annual climate variability

1. Introduction

A key objective of this report is to explore the stratospheric and tropospheric radiative forcing of climate variability and change over southern Africa, through a number of novel climate simulation experiments and dynamic-circulation analysis. An atmospheric global circulation model (AGCM), the conformal-cubic atmospheric model (CCAM), is used to perform these experiments. The main hypothesis is that the inclusion of different forms of time-dependent radiative forcing mechanisms (e.g. stratospheric ozone, greenhouse gasses, aerosols) in climate models can improve skill in simulating inter-annual variability and future climate change over southern Africa. In many state-of-the-art seasonal forecasting or climate simulation systems applied over the Southern Hemisphere, these forms of time-varying radiative forcing are not included as possible mechanisms forcing inter-annual variability – the long-term climatological averages of these forcings are used instead. One possible reason for the current situation is the assumption that seasonal forecast skill largely exists due to sea-surface temperature (SST) forcing of the atmosphere. Due to the large heat capacity of the ocean, SST forcing can be readily included in seasonal forecasting systems, using either persisted SST anomalies or predicted SSTs. Chapter 2 explores the hypothesis that the more realistic depiction of the atmosphere's ability to absorb and release radiation, through the representation of the time-varying concentrations of stratospheric ozone, greenhouse gasses and aerosols, can improve the model's skill to simulate/forecast inter-annual circulation variability. The report additionally explores the role of different radiative forcings of future climate change over southern Africa (see Chapter 3). Of key importance for the latter objective is the interplay between stratospheric ozone, which is expected to gradually recover from the currently depleted levels, and tropospheric greenhouse gas concentrations, which are expected to continue to rise steadily during the 21st century.

A number of simulations in the style of the Atmospheric Model Intercomparison Project (AMIP) have been performed to explore the impacts of time-varying radiative forcing on southern African climate. A control experiment was performed first, in which CCAM was forced with observed SSTs and climatological specifications of CO_2 and stratospheric ozone, for the period 1978-2005. In this simulation, aerosol forcing was set to zero. An ensemble of 12 members were obtained for the control experiment settings, with each member initialised using different initial conditions. These simulations were used to establish the baseline skill of the model in simulating inter-annual variability over southern Africa. Nine additional sets of AMIP-style simulations were subsequently performed, with each set consisting of 12 members and using different specifications of radiative forcing. Time-varying stratospheric ozone, CO_2 and aerosol concentrations were used to force the model in the various sensitivity tests (exact details of the nine sensitivity experiments are provided in the next section). The results obtained are presented in section 3, and conclusions are drawn in section 4.

2. The conformal-cubic atmospheric model and experimental design

CCAM is a variable-resolution global atmospheric model, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (McGregor, 1996, 2005a, 2005b; McGregor and Dix, 2001, 2008). It employs a semi-implicit semi-Lagrangian method to solve the hydrostatic primitive equations. The model includes a fairly comprehensive set of physical parameterizations. The GFDL parameterizations for long-wave and short-wave radiation are employed, with interactive cloud distributions determined by the liquid and ice-water scheme of Rotstayn (1997). A stability-dependent boundary layer scheme based on Monin Obukhov similarity theory is employed (McGregor et al., 1993), together with the non-local treatment of Holtslag and Boville (1993). A canopy scheme is included, as described by Kowalczyk et al. (1994), having six layers for soil temperatures, six layers for soil moisture (solving Richard's equation) and three layers for snow. The cumulus convection scheme uses a mass-flux closure, as described by

McGregor (2003), and includes downdrafts, entrainment and detrainment.

CCAM may be applied at quasi-uniform resolution, or alternatively in stretched-grid mode to obtain high resolution over an area of interest. Fig. 2.1 shows a quasi-uniform conformal-cubic grid, of C48 (about 200 km) resolution in the horizontal.

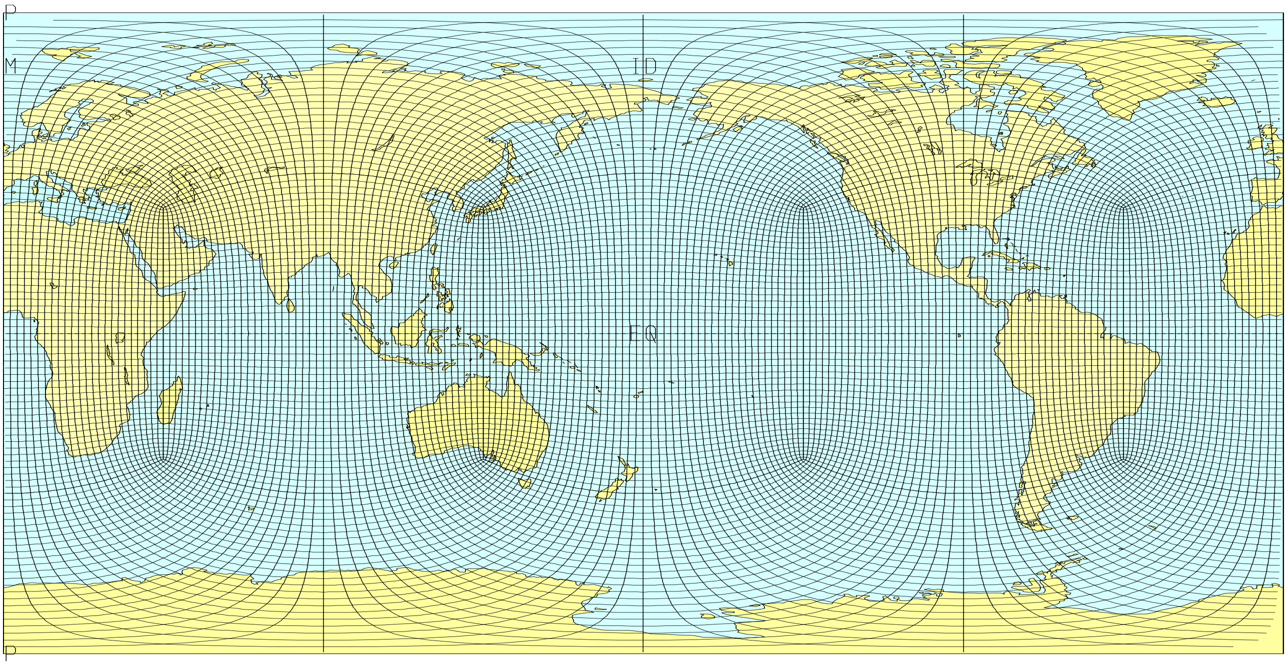

Figure 2.1: C48 quasi-uniform conformal-cubic grid, which provides a horizontal resolution of about 200 km globally.

The quasi-uniform grid displayed in Fig. 1 was employed to obtain the control experiment simulations, and for the radiative forcing simulations reported on here. In order to obtain these simulations, CCAM was forced at its lower boundary with observed monthly SST and sea-ice fields. The simulations span the period 1978 to 2005. For the control experiment, the model was forced with the climatological average concentrations of CO_2 and ozone during the integrations (as obtained from the AMIP archive), and with aerosol forcing set to zero – this is the current standard set-up when using CCAM for seasonal forecasting at the CSIR. An ensemble of simulations was obtained, using a lagged-average forecasting approach, with each ensemble member initialised during a different day of February 1978. For the case of the radiative forcing experiments, additional AMIP-style simulations were performed. The first ensemble (Radiative Forcing Experiment 1 – RFE1) was obtained following the experimental design of the control experiment, with the exception that the climatological average CO_2 concentrations were replaced with the actual observed, annually-varying values. These values were obtained from the Coupled Model Intercomparison Project Phase 3 (CMIP3) radiative forcing archive. The second ensemble (RFE2) included time-varying observed ozone concentrations as atmospheric forcing, whilst all other radiative forcings were as prescribed in the control experiment. Time-varying aerosol forcing, again following CMIP3 specifications, was applied in the third experiment (RFE3), with the CO_2 and ozone specifications as in the control experiment. A fourth experiment (RFE4) combined the time-varying forcings of CO_2, ozone and aerosols as described in RFE1 to RFE3. In the control experiment and RFE2 to RFE4 CCAM was applied with 18 levels in the vertical. The remaining five sensitivity experiments were performed using the 27-level version of the model and a more sophisticated version of the radiation scheme. The first of these experiments mirrored the design of the control experiment, with the only difference being the use 27 levels in the vertical and the modified radiation scheme (RFE5). The second 27-level experiment (RFE6) mirrored the design of RFE5, but with the climatological CO_2 values replaced by the observed time-varying values as described by the Coupled Model Intercomparison Project Phase Five (CMIP5). A third 27-level experiment (RFE7) used the time-varying ozone values provided by CMIP5, with other forcings as in RFE5. The fourth 27-level experiment mirrored the design of RFE5, but with time-varying aerosol emissions as prescribed by CMIP5 (RFE8). The final radiative forcing experiment also made use of the 27-level set-up, and with time-varying CO_2, ozone and aerosol forcings as described by CMIP5 (RFE9). It may be noted that performing the simulations was computationally and time-intensive, and relied in the use of a computer cluster of the Centre for High Performance Computing (CHPC) of the CSIR. A schematic presentation of the radiative forcing experiments is provided in Table 1.

Table 1: Schematic outlay of the radiative forcing experiments

Experiment	**Forcing Archive**	**CO_2**	**Ozone**	**Aerosols**
Control	AMIP	climatological	climatological	set to zero
RFE1	CMIP3	time-varying	climatological	set to zero
RFE2	CMIP3	climatological	time-varying	set to zero
RFE3	CMIP3	climatological	climatological	time-varying
RFE4	CMIP3	time-varying	time-varying	time-varying
RFE5	AMIP	climatological	climatological	climatological
RFE6	CMIP5	time-varying	climatological	set to zero
RFE7	CMIP5	climatological	time-varying	set to zero
RFE8	CMIP5	climatological	climatological	time-varying
RFE9	CMIP5	time-varying	time-varying	time-varying

3. Results and insights from the radiative forcing simulations

3.1 Simulating inter-annual variability: the control experiment (AMIP specifications)

The model skill in simulating summer 850 hPa geopotential anomalies over southern Africa in the control simulation is shown in Figure 2.2. Skill is measured in terms of the Ranked Probability Score (RPS), where the reference RPS values are based on the climatological probabilities (for the occurrence of the events in below-normal, normal or above-normal categories, as defined by terciles). Positive values indicate that the model simulations have skill over the reference forecasts based on climatology, whilst negative values are indicative of areas where the model forecasts are not skilful over climatology. The main findings can be summarised as follows:

- The simulations of summer circulation anomalies (Fig. 2.2 top left) are highly skilful, with maximum skill found over the interior regions of southern and tropical Africa.

- The simulations are less skilful over the western parts of southern Africa, but are still skilful over climatology.

- The simulations are the least skilful over the Southern Ocean, where the westerly wind regime and fast-propagating frontal systems prevail.

- The model skill in simulating austral autumn 850 hPa geopotential anomalies over southern Africa in the control simulation is shown in Fig. 2.2 (top right).

- The simulations are skilful across southern Africa for the austral autumn period (Fig. 2.2 top right), but are significantly less skilful than the simulations for the summer months.

- Simulation skill is higher for tropical Africa compared to southern Africa, and skill is particularly low over the southern part of South Africa.

- The simulations for the austral winter are skilful across southern Africa (Fig. 2.2 bottom left), but are significantly less skilful than the simulations for the summer months.

- Simulation skill is the highest for the western interior regions of southern Africa, and is relatively high over the winter rainfall region of southern South Africa compared to the oceanic regions to the south.

- The simulations for the austral spring are skilful across southern Africa (Fig. 2.2 bottom right), but are significantly less skilful than the simulations for the summer months.

3.2 RFE1 – Simulating inter-annual variability: the effects of time-varying CO_2 (CMIP3 specifications)

Fig. 2.3 shows the change in skill obtained through the introduction of time-varying CO_2 forcing. Here the control experiment simulations are used to define the reference simulation in the calculations of the skill score based on the RPS. Related work performed as part of this project has demonstrated that the inclusion of time-varying CO_2 concentrations in CCAM AMIP simulations lead to a significant improvement in the simulation of observed trends in surface temperature over southern Africa (see Chapter 4).

For the summer and spring seasons, simulation skill for the ensemble employing time-varying CO_2 is generally higher than that of the control simulation over the African continent. During the summer season, solar radiative forcing peaks over southern Africa and it is plausible that the effects of time-varying CO_2 forcing will be of the most significance during this season. It is difficult to explain the reductions in skill that result from the inclusion of more realistic CO_2 forcing for the autumn and winter seasons. However, the baseline skill levels as depicted by the control experiment (Figure 2.3 are already relatively low (compared to the summer seasons), which reduces the importance of these results.

3.3 RFE2 – Simulating inter-annual variability: the effects of time-varying ozone (CMIP3 specifications)

The inclusion of time-varying ozone at the expense of climatological ozone leads to an improvement in simulation skill over most of Africa for spring and summer (Fig. 2.4). Most prominent is a band of improved skill occurring over the Southern Ocean to the south of South Africa in spring. This region of high skill appears to propagate to the summer rainfall region of South Africa in summer. These results are consistent with the existing understanding that stratospheric ozone forcing in spring over Antarctica has a chain reaction in the middle latitudes lasting into the summer months. The reductions in skill resulting over the central and northern parts of Africa that result from the inclusion of time-varying stratospheric ozone for the autumn and winter seasons may suggest that the specification of time-varying ozone values in the tropics and subtropics is deficient. This is an aspect that requires further investigation in future model development research to be performed at the CSIR.

3.4 RFE3 – Simulating inter-annual variability: the effects of time-varying aerosols (CMIP3 specifications)

The inclusion of prognostic aerosols leads to an increase in simulation skill over most of tropical and southern Africa for summer (Figure 2.5), and to some extent also for spring. For the winter and autumn seasons, reductions in skill can be observed over most of the domain Africa. For the winter season, this may be the result of the inadequate representation of biomass burning aerosols that are most abundant over southern Africa in winter.

3.5 RFE4 – Simulating inter-annual variability: the combined effects of time-varying CO_2, ozone and aerosols (CMIP3 specifications)

The effects of combining the three forms of radiative forcing do not yield net gains in skill, as improvements gained in skill from the individual forcings are not superimposed. Rather, nonlinear interactions lead to the reduction in skill in some regions and improvements in others, compared to the control experiment (Figure 2.6). Perhaps the most important result is improved skill over the Southern Ocean for all the seasons, with the region of higher skill propagating to southern Africa in summer. That is, the effects of time-varying ozone forcing is preserved in experiment that combines all time-varying forcings.

3.6 RFE5 – Simulating inter-annual variability: the 27-level model with climatological forcings (AMIP specifications)

The simulations with the 27-level version of the model using climatological radiative forcings as specified by AMIP are displayed in Fig. 2.8. The 27-level simulation produced a mixed signal of improved and decreased skill across the different seasons, and over space. It should be noted, however, that this version of the model was developed for the case of CMIP5 radiative forcing. The extended radiation scheme for the 27-level version of the model, in particular, has been developed using the CMIP5 specifications of time-varying CO_2 and ozone. It may therefore be expected that application of the 27-level version of the model will produce higher skill when forced with CMIP5 radiative forcing fields (see the following subsections).

3.7 RFE6 – Simulating inter-annual variability: the 27-level model with time-varying CO_2 (CMIP5 specifications)

Fig. 2.8 shows the change in skill obtained through the introduction of time-varying CO_2 forcing following CMIP5 specifications. For the summer season, simulation skill for the ensemble employing time-varying CO_2 is generally higher than that of the control simulation over the African continent. During the summer season, solar radiative forcing peaks over southern Africa and it is plausible that the effects of time-varying CO_2 forcing will be of the most significance during this season (consistent results were obtained using the 18-level version of the model). It is difficult to explain the reductions in skill that result from the inclusion of more realistic CO_2 forcing for the autumn and winter seasons (and to a lesser extent for spring). However, the baseline skill levels as depicted by the control experiment (Figure 2.2 are already relatively low (compared to the summer season), which reduces the importance of these findings.

3.8 RFE7 – Simulating inter-annual variability: the effects of time-varying ozone (CMIP5 specifications)

The inclusion of time-varying ozone at the expense of climatological ozone leads to an improvement in simulation skill over the southern and tropical Africa for summer in the 27-level version of the model (Fig. 2.9), compared to the control experiment (Fig. 2.2). Consistent with the 18-level results, there is a band of improved skill occurring over the Southern Ocean to the south of South Africa in spring that apparently propagates to the north in summer. These results are consistent with the existing understanding that stratospheric ozone forcing in spring over Antarctica has a chain reaction in the middle latitudes lasting into the summer months. The reductions in skill resulting over the central and northern parts of Africa that result from the inclusion of time-varying stratospheric ozone for the autumn and winter seasons may suggest that the specification of time-varying ozone values in the tropics and subtropics is deficient (consistent results were obtained using the 18-level version of the model with CMIP3 ozone forcing). This is an aspect that requires further investigation in future model development research to be performed at the CSIR.

3.9 RFE8 – Simulating inter-annual variability: the effects of time-varying aerosols (CMIP5 specifications)

The inclusion of prognostic aerosols (CMIP5 specifications) leads to an increase in simulation skill over most of tropical Africa and the eastern parts of southern Africa for summer (Figure 2.10). Similar improvements are present for spring and over tropical Africa for winter. For the autumn season, reductions in skill can be observed over most of tropical Africa. The results obtained with the 27-level version of the model and CMIP5 forcings is to a large extent consistent with those obtained with the 18-level version of the model and CMIP3 forcings.

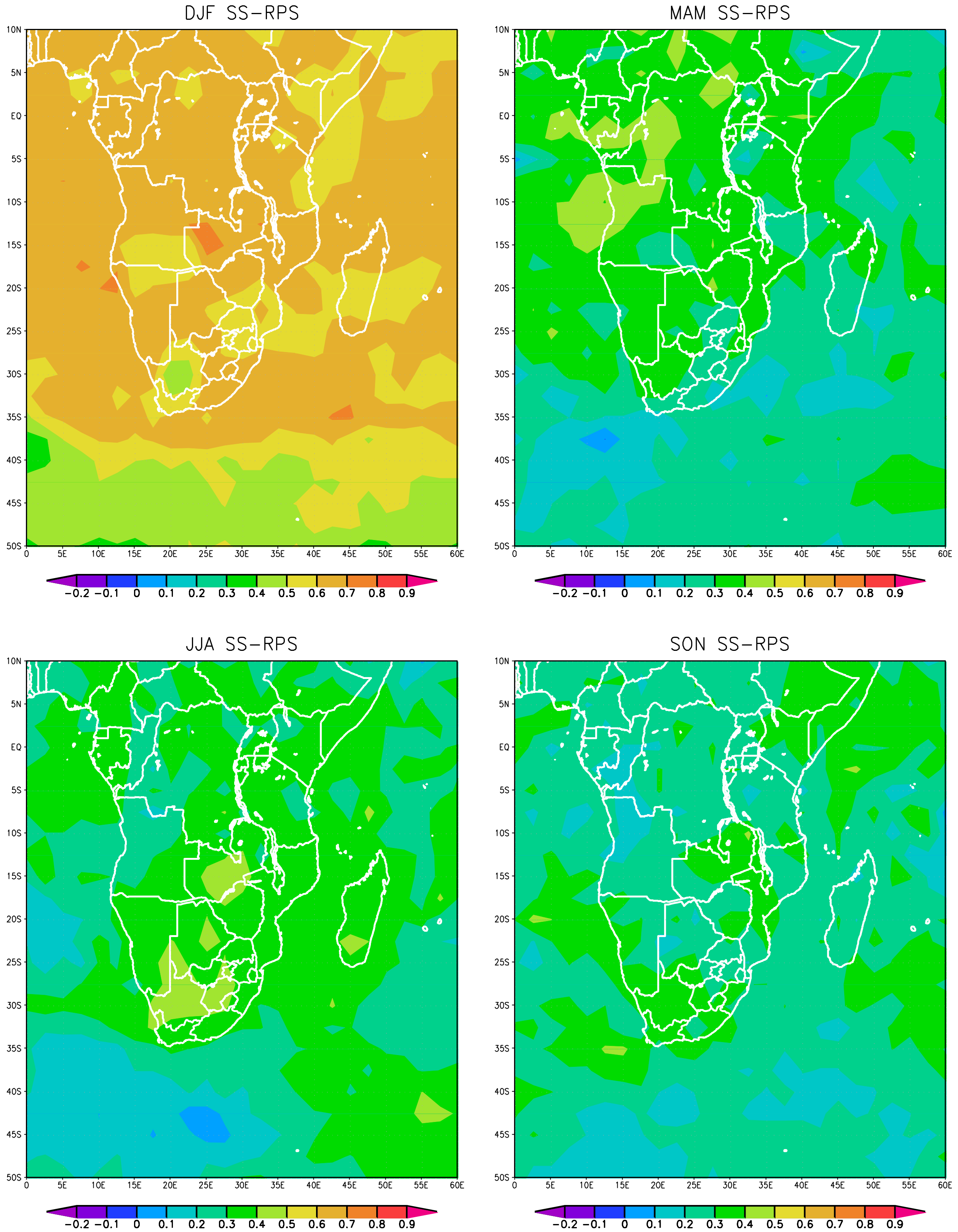

Figure 2.2: CCAM skill in simulating seasonal 850 hPa geopotential height anomalies over southern Africa, for the control experiment forced with climatological radiative forcings (as specified by AMIP). The figure shows the skill score based on the Ranked Probability Score (RPS), with climatological circulation used as the reference forecast.

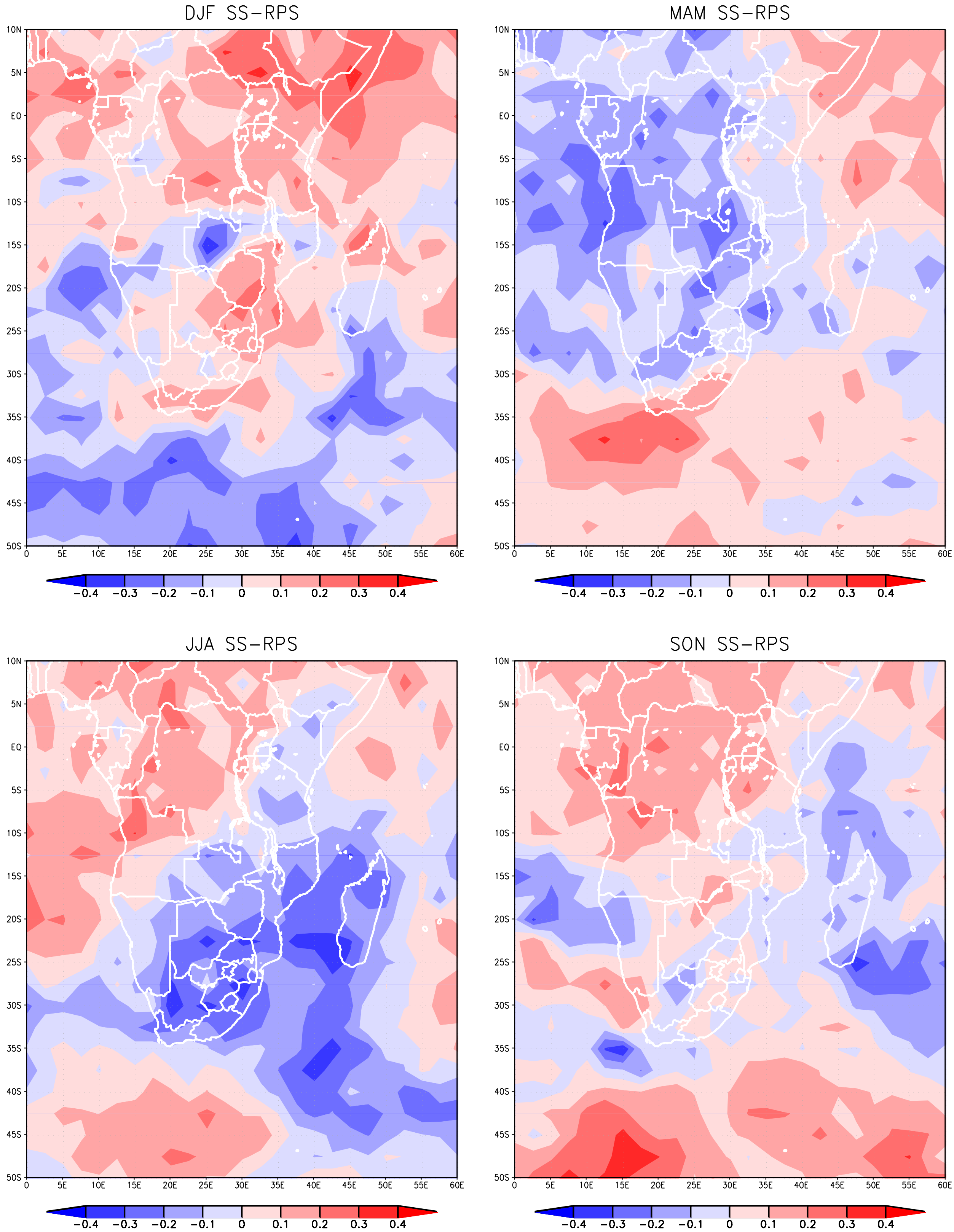

Figure 2.3: Change in CCAM skill in simulating seasonal 850 hPa geopotential anomalies over southern Africa, for the case of time-varying CO_2 forcing (as specified by CMIP3) relative to climatological radiative forcings (RFE1). Here the change in skill is depicted in terms of the skill score based on the RPS, but with the CCAM simulations of the control experiment used as the reference forecast.

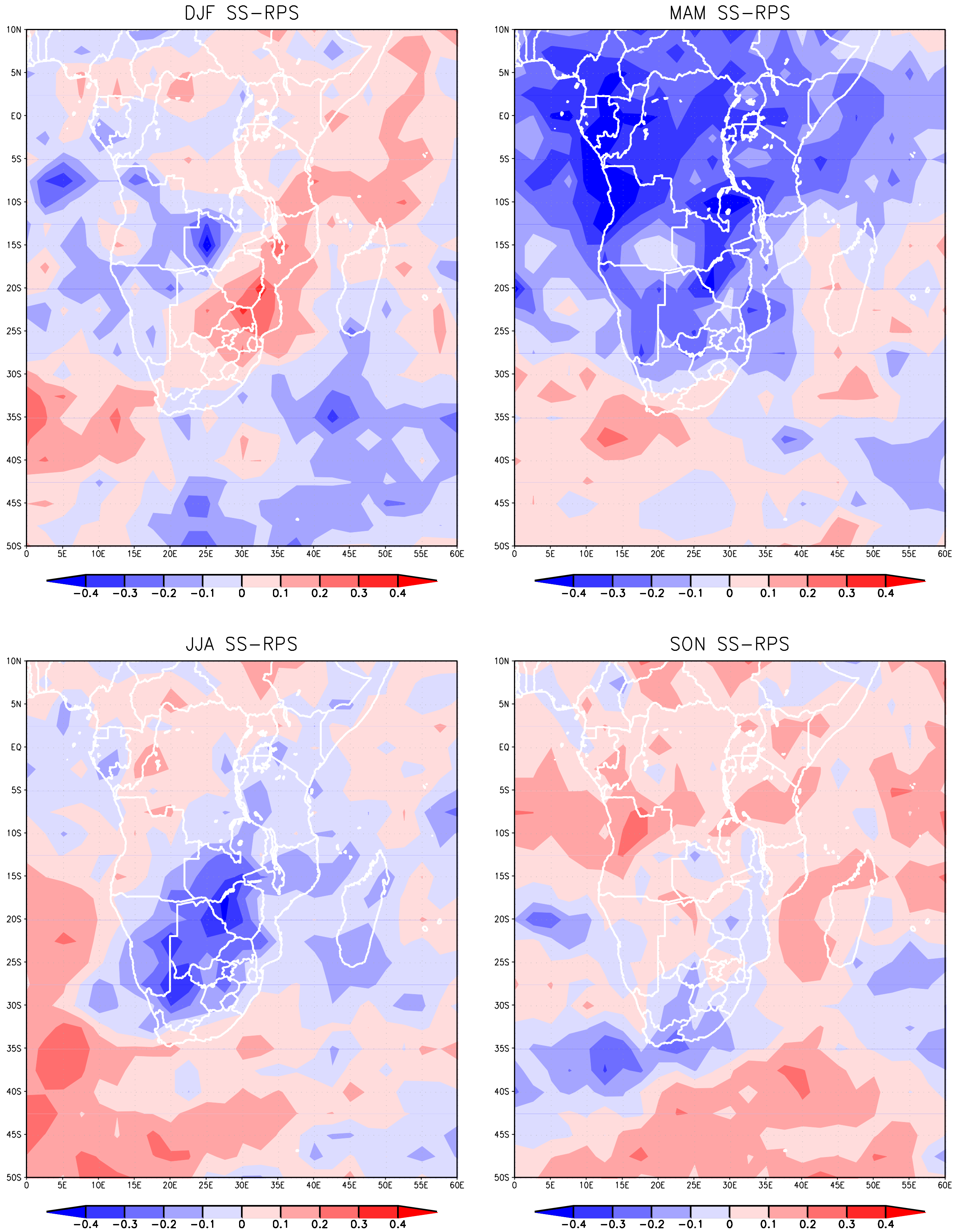

Figure 2.4: Change in CCAM skill in simulating seasonal 850 hPa geopotential anomalies over southern Africa, for the case of time-varying stratospheric ozone forcing (as specified by CMIP3) relative to climatological radiative forcings (experiment RFE2). Here the change in skill is depicted in terms of the skill score based on the RPS, but with the CCAM simulations of the control experiment used as the reference forecast.

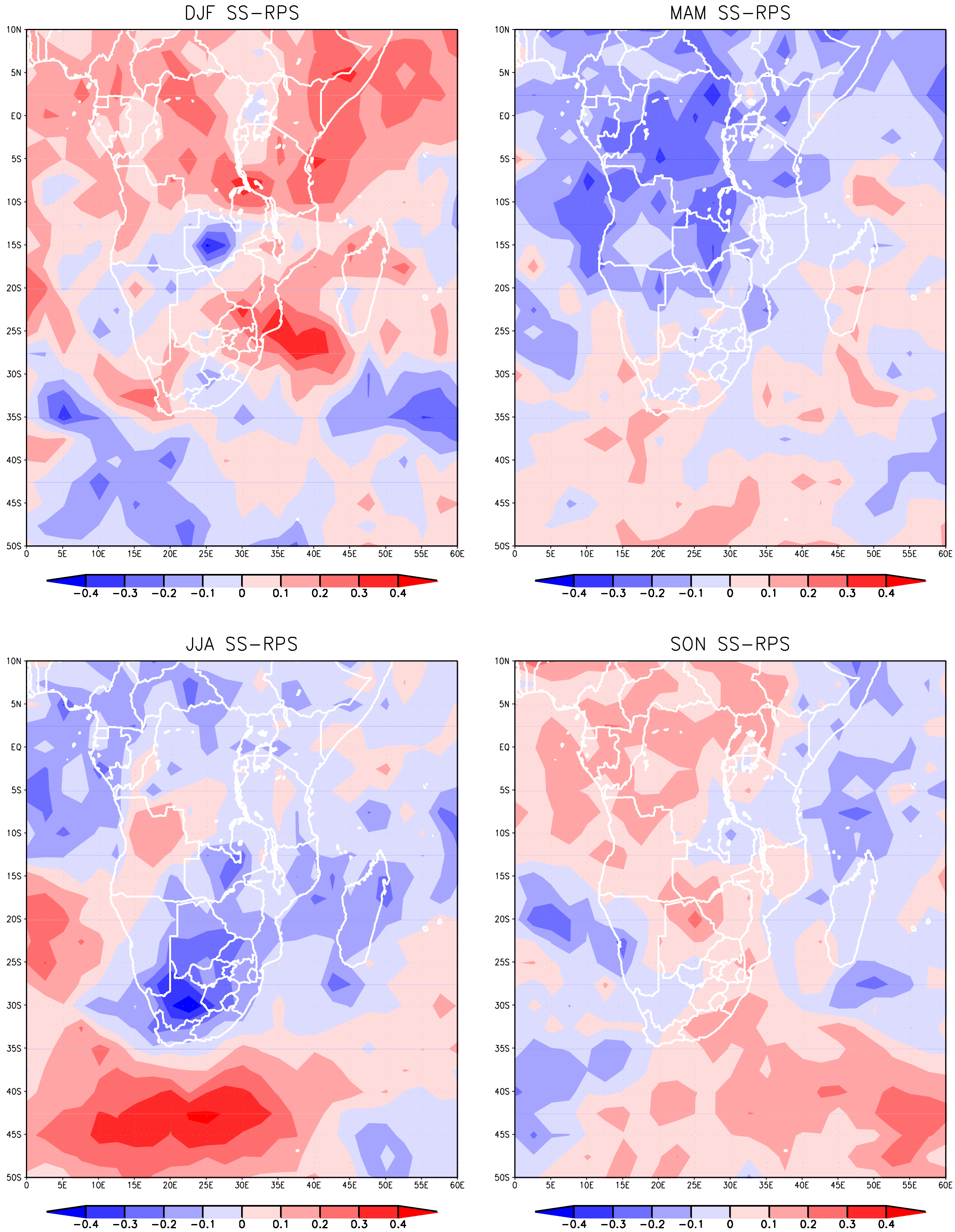

Figure 2.5: Change in CCAM skill in simulating seasonal 850 hPa geopotential anomalies over southern Africa, for the case of prognostic aerosol forcing (as specified by CMIP3) relative to climatological radiative forcings (experiment RFE3). Here the change in skill is depicted in terms of the skill score based on the RPS, but with the CCAM simulations of the control experiment used as the reference forecast.

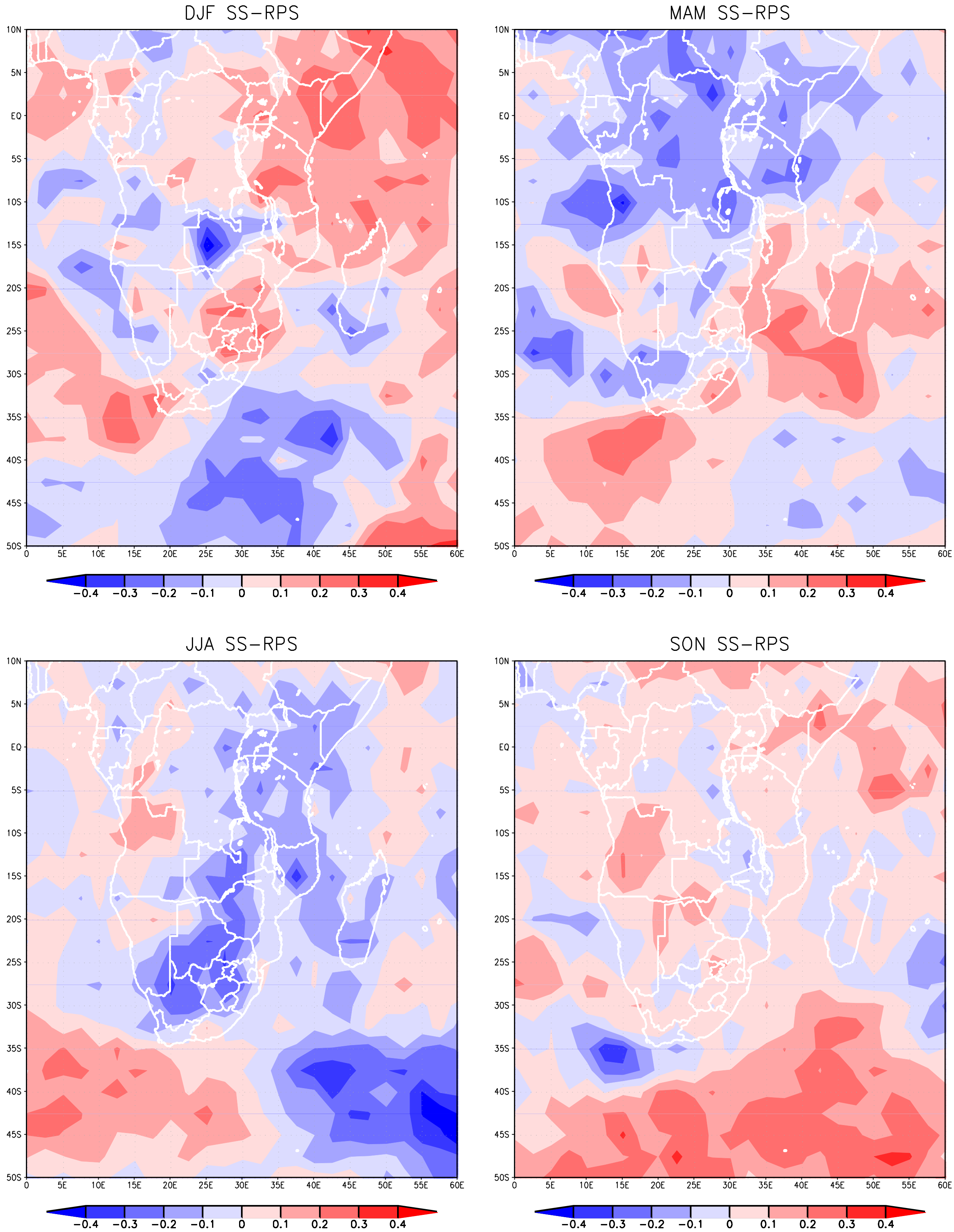

Figure 2.6: Change in CCAM skill in simulating seasonal 850 hPa geopotential anomalies over southern Africa, for the case of time-varying CO_2, stratospheric ozone and aerosol forcing (as specified by CMIP3) relative to climatological radiative forcings (experiment RFE4). Here the change in skill is depicted in terms of the skill score based on the RPS, but with the CCAM simulations of the control experiment used as the reference forecast.

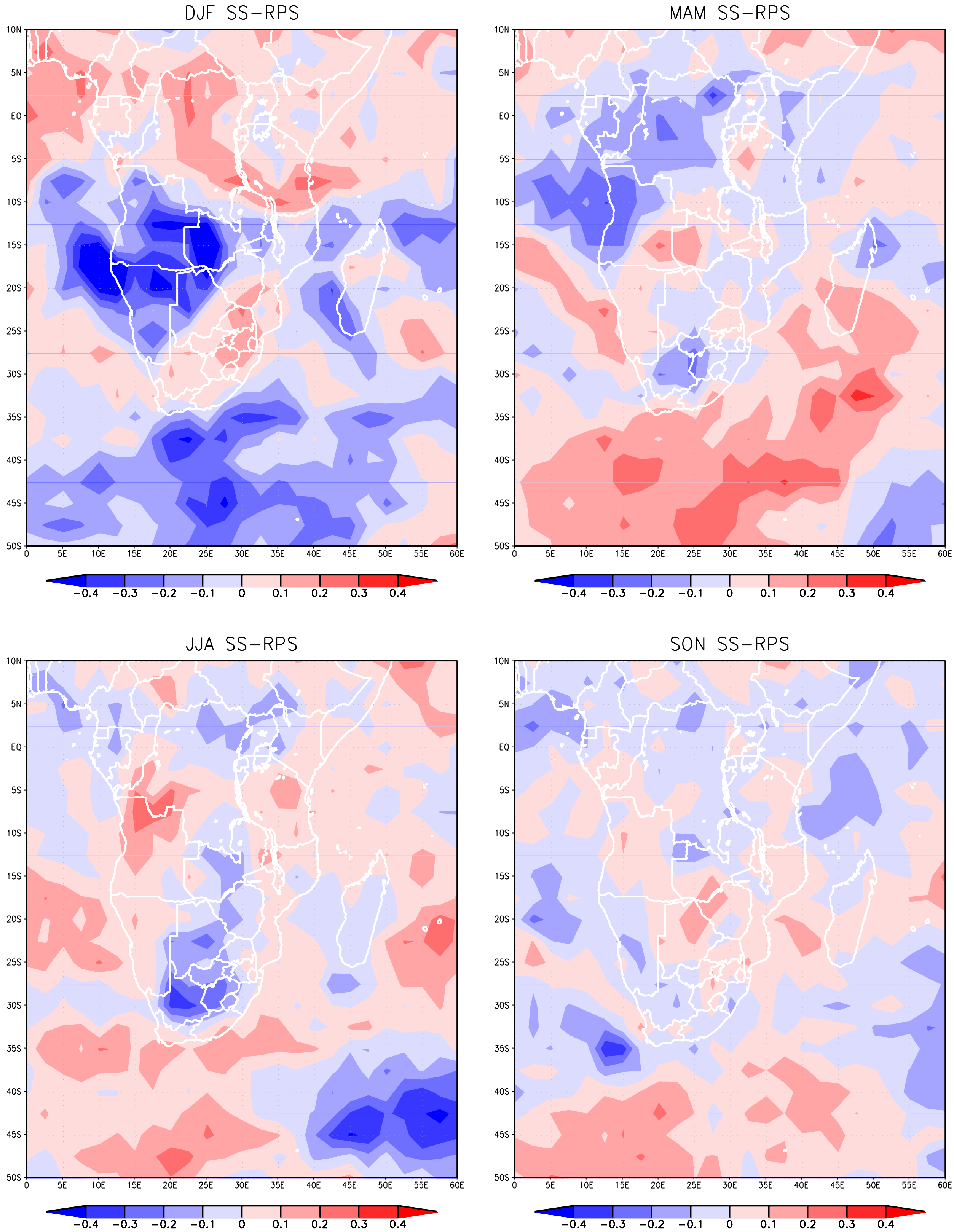

Figure 2.7: Change in CCAM skill in simulating seasonal 850 hPa geopotential anomalies over southern Africa, for the case of climatological radiative forcings (as described by AMIP) using the 27-level version of the model (experiment RFE5). Here the change in skill is depicted in terms of the skill score based on the RPS, but with the CCAM simulations of the control experiment used as the reference forecast.

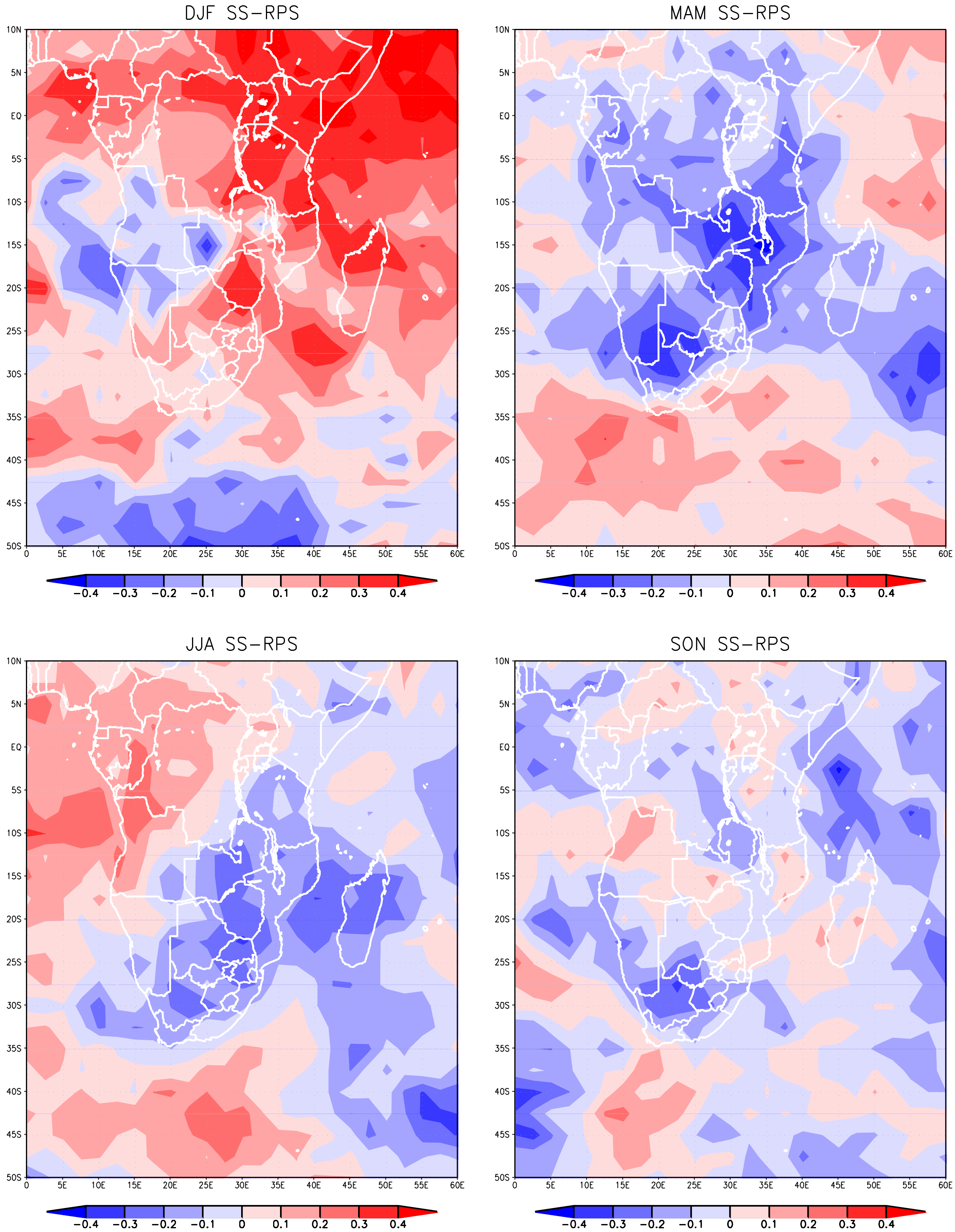

Figure 2.8: Change in CCAM skill in simulating seasonal 850 hPa geopotential anomalies over southern Africa, for the case of time-varying CO_2 (as described by CMIP5) using the 27-level version of the model (experiment RFE6). Here the change in skill is depicted in terms of the skill score based on the RPS, but with the CCAM simulations of the control experiment used as the reference forecast.

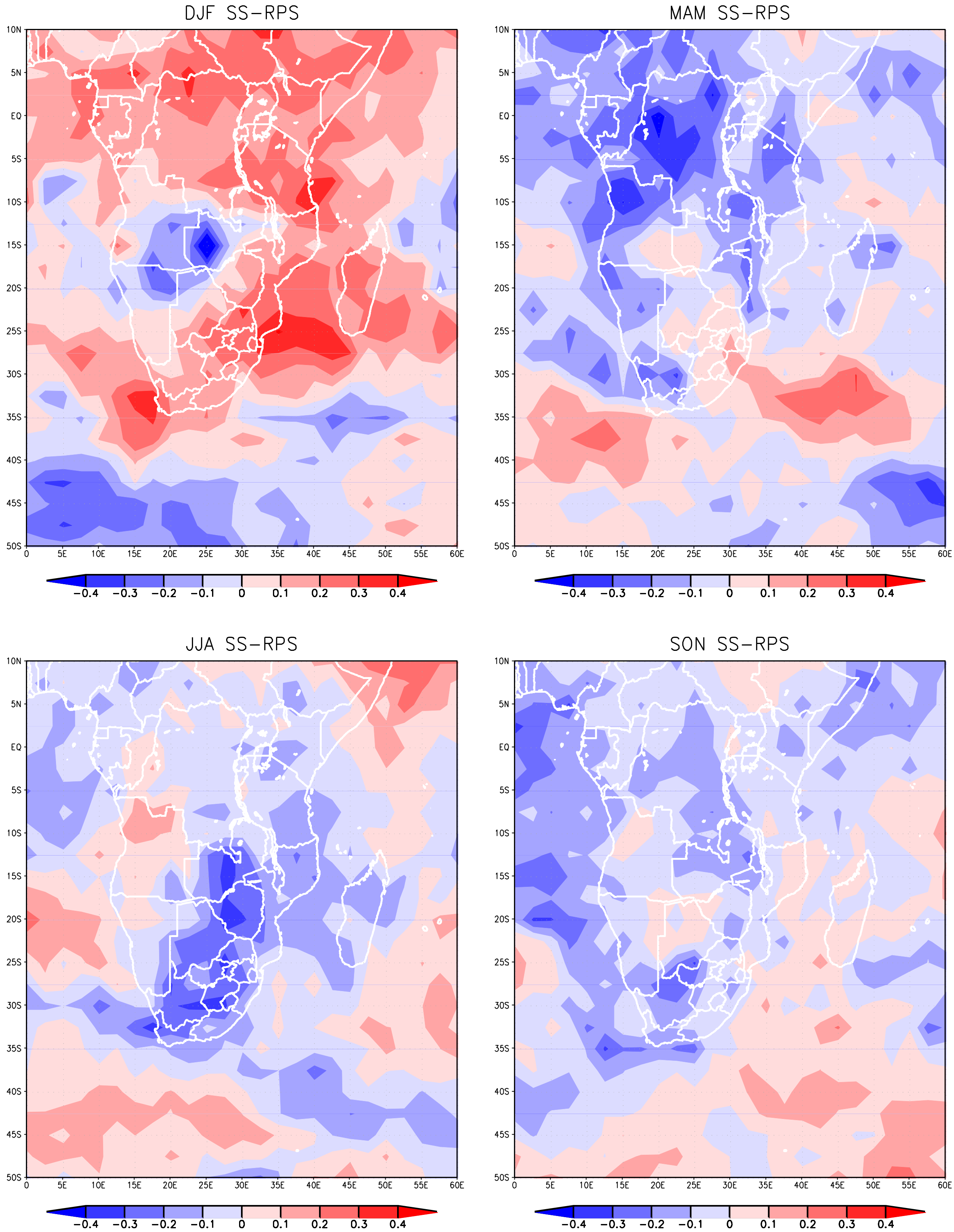

Figure 2.9: Change in CCAM skill in simulating seasonal 850 hPa geopotential anomalies over southern Africa, for the case of time-varying ozone (as described by CMIP5) using the 27-level version of the model (experiment RFE7). Here the change in skill is depicted in terms of the skill score based on the RPS, but with the CCAM simulations of the control experiment used as the reference forecast.

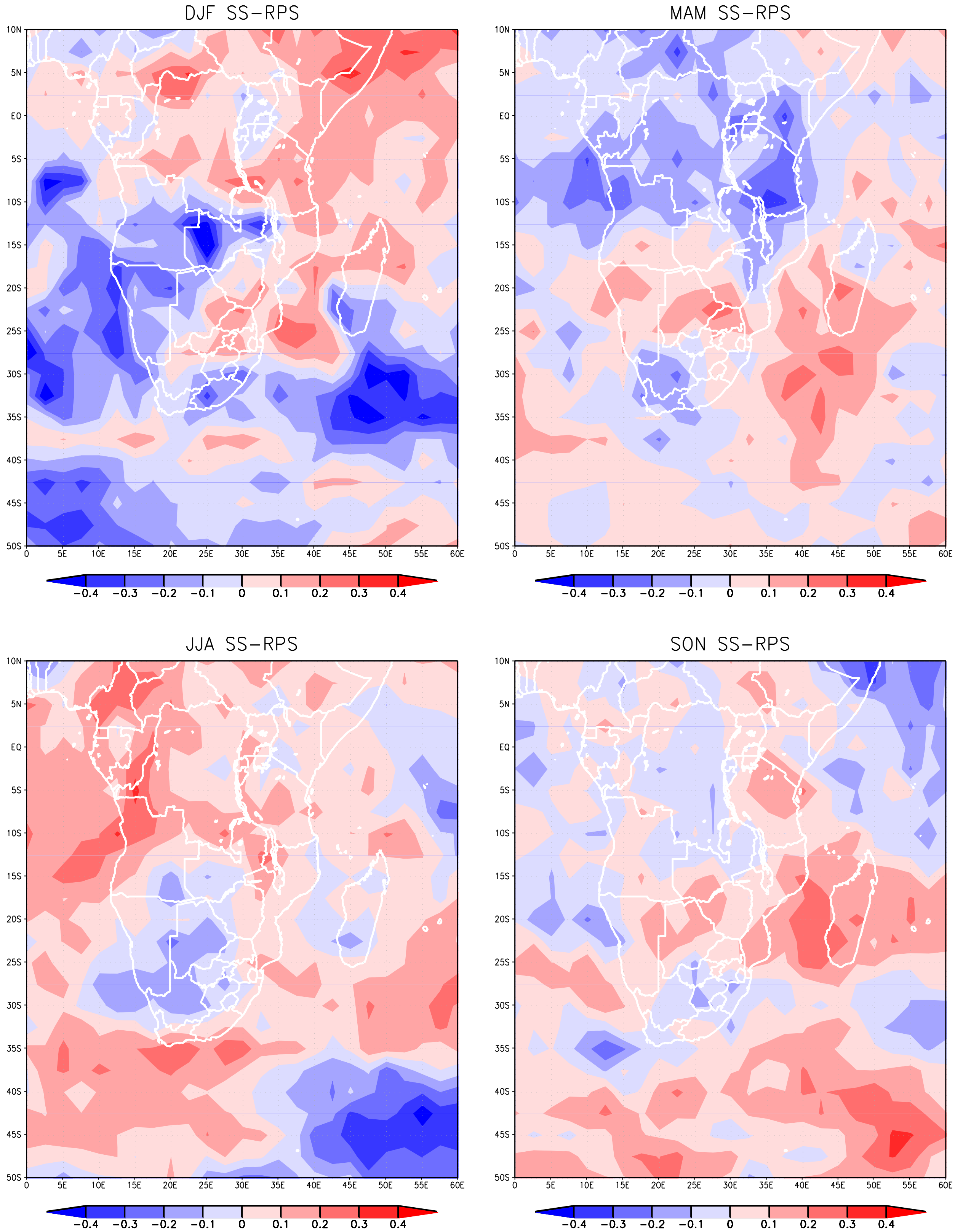

Figure 2.10: Change in CCAM skill in simulating seasonal 850 hPa geopotential anomalies over southern Africa, for the case of time-varying aerosols (as described by CMIP5) using the 27-level version of the model (experiment RFE8). Here the change in skill is depicted in terms of the skill score based on the RPS, but with the CCAM simulations of the control experiment used as the reference forecast.

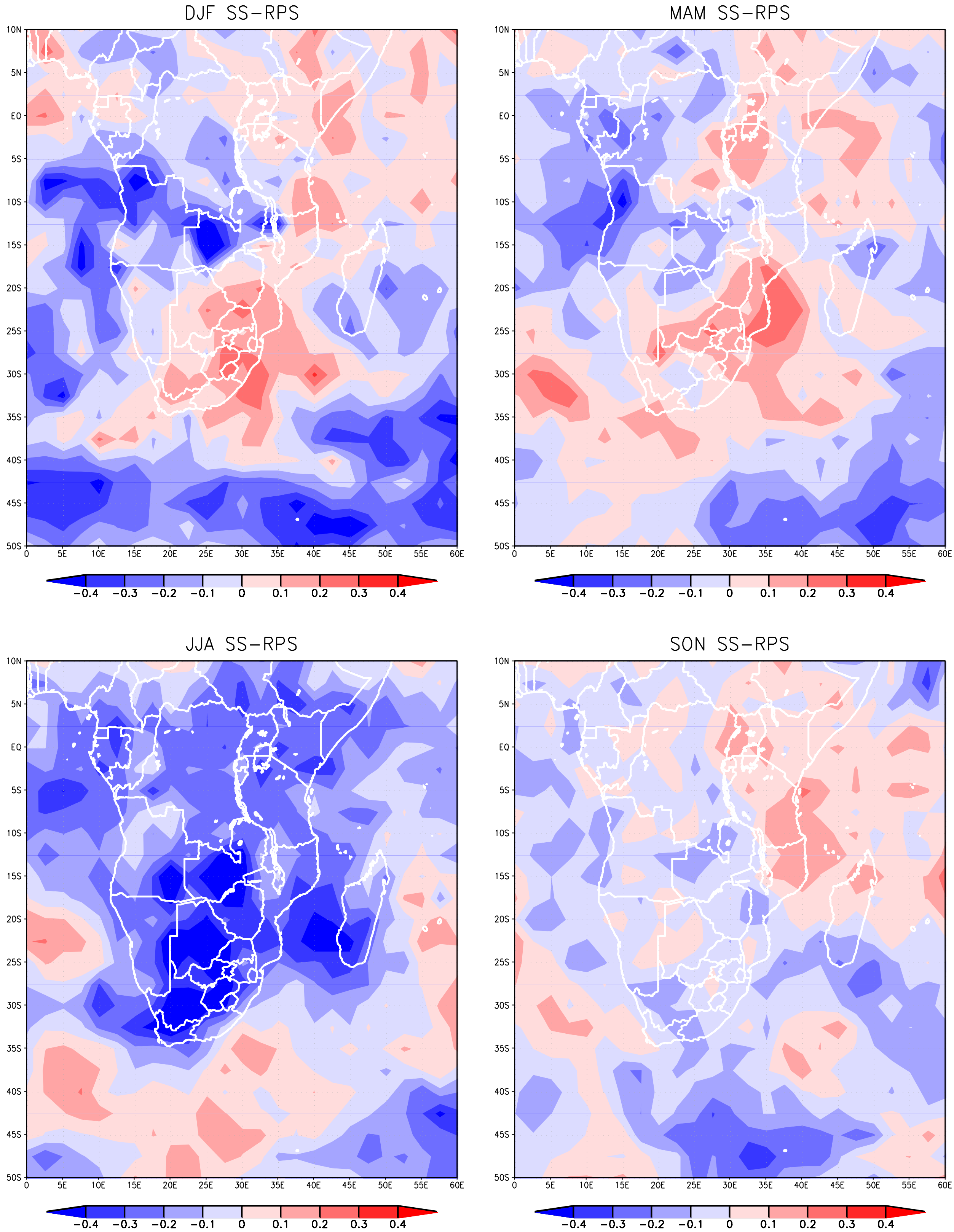

Figure 2.11: Change in CCAM skill in simulating seasonal 850 hPa geopotential anomalies over southern Africa, for the case of time-varying ozone, CO_2 and aerosols (as described by CMIP5) using the 27-level version of the model (experiment RFE9). Here the change in skill is depicted in terms of the skill score based on the RPS, but with the CCAM simulations of the control experiment used as the reference forecast.

3.10 RFE9 – Simulating inter-annual variability: the combined effects of time-varying CO2, ozone and aerosols (CMIP5 specifications)

The effects of combining the three forms of radiative forcing do not yield net gains in skill, as improvements gained in skill from the individual forcings are not superimposed. Rather, nonlinear interactions lead to a reduction in skill in some regions and improvements in others (Fig. 2.11), compared to the control experiment (Fig. 2.2). Perhaps the most important result is improved skill over the summer rainfall region in summer. This may imply that the ozone-induced improvements in skill (Fig. 2.9) is preserved in this experiment that combines all CMIP5 prescribed forcings.

4. Summary

The AGCM CCAM was used to perform AMIP-style simulations designed to investigate the effects of the inclusion of time-varying radiative forcing on improving model skill in representing the inter-annual variability of the seasonal circulation anomalies over southern Africa. More specifically, the effects of using realistic, time-varying radiative forcings (ozone, CO_2 and aerosols concentrations) were investigated by a comparison to a control experiment where climatological radiative forcings were used. Two main sets of radiative forcing simulations were performed. The first used the 18-level version of CCAM, with radiative forcings described using the CMIP3 archive. The second used the 27-level version of CCAM, with radiative forcings described by CMIP5. The main findings from the radiative forcing experiments are:

- The simulations of the inter-annual variability of seasonal circulation anomalies are most skilful for the austral summer in the control experiment. This result provides some insight into the relatively high levels of skill reported in general for the prediction of summer rainfall totals over southern Africa at the seasonal time-scale compared to other seasons (this skill stems from the underlying circulation fields being forecasted skilfully for summer). The drastic reduction in skill that occurs in the autumn, winter and spring seasons over southern Africa may be at least partially attributed to the northward-displaced westerlies, with its transient weather systems of which the variability is simulated less skilfully. Another important contributing factor may be that ENSO related SST anomalies are generally the largest during the early summer, with important regional SST anomalies such as those associated with the South Indian Ocean subtropical dipole being the largest in the late summer (Reason et al., 2000). That is, the abilities of the tropical Pacific Ocean and regional oceans to force climate variability over southern Africa are reduced outside the austral summer. The relatively low skill of the model in simulating the inter-annual variability in autumn, winter and spring circulation over southern Africa is an important finding of the project, as the postulated underlying reasons for this low skill imply that improvements in forecast skill for these seasons may be extremely difficult to attain (and should not be sought in the first place through parameterisations, e.g. convective rainfall parameterisations).
- The inclusion of time-varying stratospheric ozone concentrations improves the simulation skill of circulation variability over the Southern Ocean in spring, and over southern Africa in summer. This is perhaps the most significant finding of the radiative forcing experiments. This result is fully consistent with dynamic circulation theory, according to which stratospheric forcing over Antarctica in spring has a pronounced mid-latitude response in summer. This study is the first to demonstrate that this response actually reaches the subtropical latitudes of southern Africa (also see Chapter 5).
- The inclusion of time-varying CO_2 concentrations offer some benefit for the simulation of summer-time inter-annual variability, particularly in the tropics. The simulated changes in skill are, however, negative for most other seasons and regions.
- The prognostic treatment of aerosols is problematic in the model simulations for winter, and leads to decreases simulation skill over the southern African interior. However, the inclusion of prognostic aerosols leads to an increase in simulation skill over most of tropical and southern Africa for summer and spring.

Chapter 3
Projections of future climate change over the Southern Hemisphere and southern Africa: the relative roles of the enhanced greenhouse effect and recovering stratospheric ozone

1. Introduction

Climate change is projected to impact drastically in southern African during the 21st century under low mitigation futures (Niang et al., 2014). African temperatures are projected to rise rapidly, at 1.5 to 2 times the global rate of temperature increase (James and Washington, 2013; Engelbrecht et al., 2015). Moreover, the southern African region is projected to become generally drier under enhanced anthropogenic forcing (Christensen et al., 2007; Engelbrecht et al., 2009; James and Washington, 2013; Niang et al., 2014). These changes in the annual and seasonal rainfall patterns will plausibly have a range of impacts in South Africa, including impacts on energy demand (in terms of achieving human comfort within buildings and factories), agriculture (e.g. reductions of yield in the maize crop under higher temperatures and reduced soil moisture), livestock production (e.g. higher cattle mortality as a result of oppressive temperatures) and water security (through reduced rainfall and enhanced evapotranspiration) (e.g. Engelbrecht et al., 2015).

Simulating present-day and future climate change is of course a problem in radiative forcing. For the Southern Hemisphere, the interplay between the enhanced greenhouse effect and recovering stratospheric ozone levels is of key importance. Over the last few decades, the enhanced greenhouse effect and stratospheric ozone depletion have both contributed to the poleward displacements of the westerlies (e.g. Thompson and Solomon, 2002; also see Chapter 5). However, the recovery of stratospheric ozone that is expected to occur during the first half of the 21st century may eventually function to counteract the continued poleward displacement of the westerlies (Eiring et al., 2007). The purpose of this Chapter is to explore the relative importance of these two forms of radiative forcing in terms of future southern African climate change.

2. Results from the radiative forcing simulations – trends in present-day temperatures

The temperature trends observed over southern Africa, over the period 1979-2005, are displayed in Fig. 3.1 (top). Very strong trends in temperature, in the order of 2°C/century or more, have occurred over the subtropical and western parts of the subcontinent during this time – presumably in response to the enhanced greenhouse effect. This result has been obtained through analysis of a 5° resolution observed temperature data set CRUTEMv of the Climatic Research Unit (CRU), which consists of variance-adjusted homogeneous time-series, constructed specifically for the analysis of temperature trends. Trends were calculated using the method of pairwise slopes, whilst the statistical significance of the trends can be deduced from the associated Spearman rank correlations (Fig. 3.1, bottom – also see Engelbrecht et al. (2015)).

Fig. 3.2 (top) shows the trends in annual average temperature over southern Africa as simulated in the control experiment (where greenhouse gas and ozone concentrations were kept constant over time for the simulation period 1978 to 2005. The associated Spearman rank correlations are displayed in the lower panel. It can be seen that the simulated temperature trends bear little resemblance to observations. Temperature trends simulated over the western interior, for example, are very weak compared to the strong positive trends recorded over this region. The Spearman rank correlations of the simulated trends are also relatively low, indicating that the simulated trends are generally not statistically significant. These results may be considered important – apparently, a climate-variability simulation system (or seasonal forecasting system) relying only on SST and sea-ice forcing is not capable of simulating temperature trends (and possibly associated inter-annual temperature variability) over the southern African region – even though the SSTs themselves have been steadily increasing under the enhanced greenhouse effect. The results point towards the importance of having realistically varying greenhouse gas concentrations in the simulations. This would provide the model atmosphere with the ability to more realistically absorb heat released

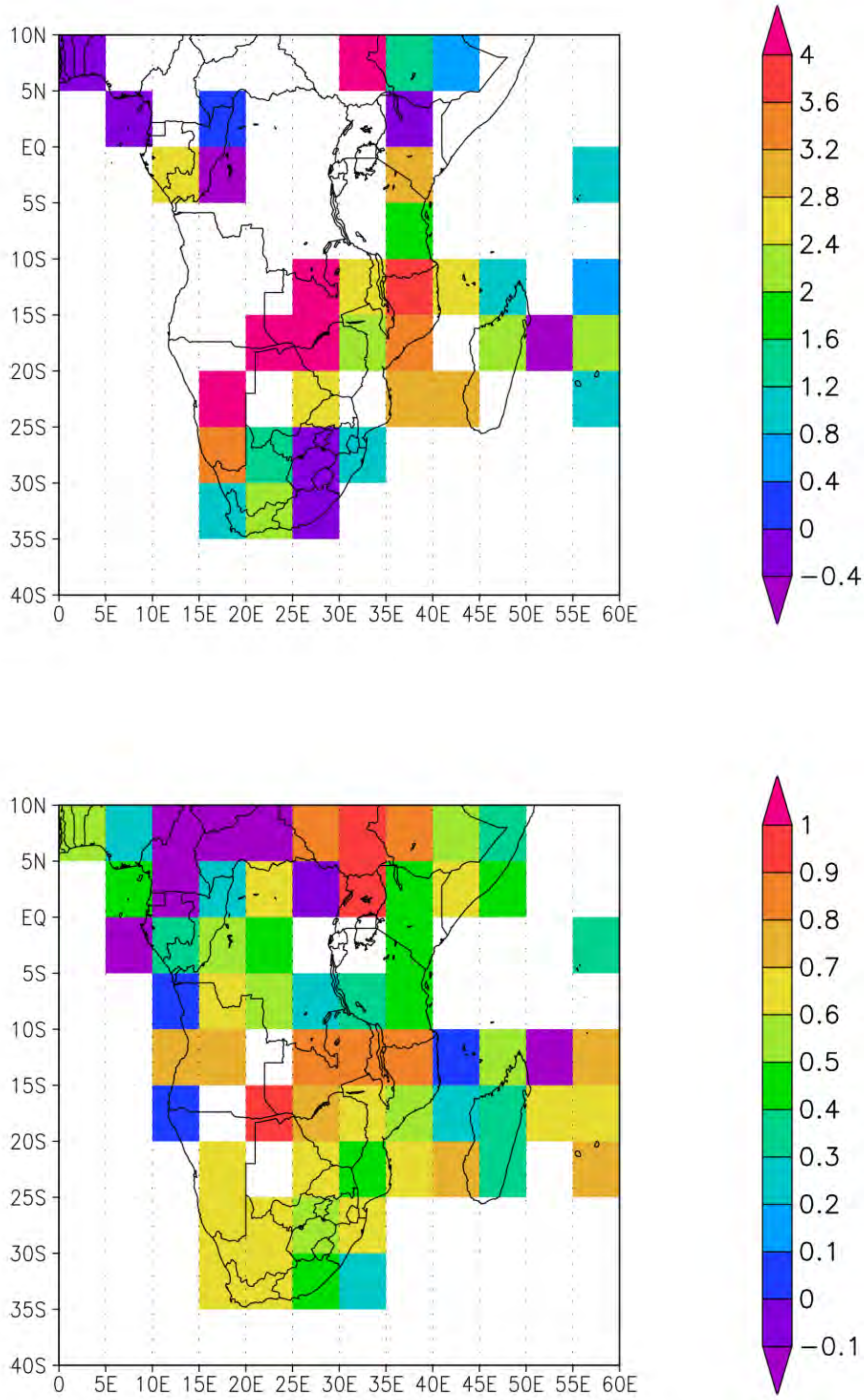

Figure 3.1: Observed temperature trends over southern Africa (top panel, units: °C/century) for the period 1979-2005, as calculated from CRU variance-adjusted data. The associated Spearman rank correlations are shown in the lower panel.

from the oceans in the gradually warming planet. Such simulations have been performed as part of the radiative forcing experiments described in Chapter 2 (see, for example, RFE1). Figure 3.3 shows the trends in simulated annual average temperature over southern Africa, from the AMIP-style experiment RFE1 (see Table 1) where the actual observed, time-varying CO_2 concentrations were used to force the model over the period February 1978 to December 2005. The associated Spearman rank correlations are displayed in the lower panel. It can be seen that the simulated temperature trends are significantly higher than in the case of the control experiment (Fig. 3.2), where greenhouse gas concentrations were kept constant during the simulations. Temperature trends over the subtropical parts of southern Africa, for example, are significantly higher than in the control experiment and bear much closer correspondence to observations.

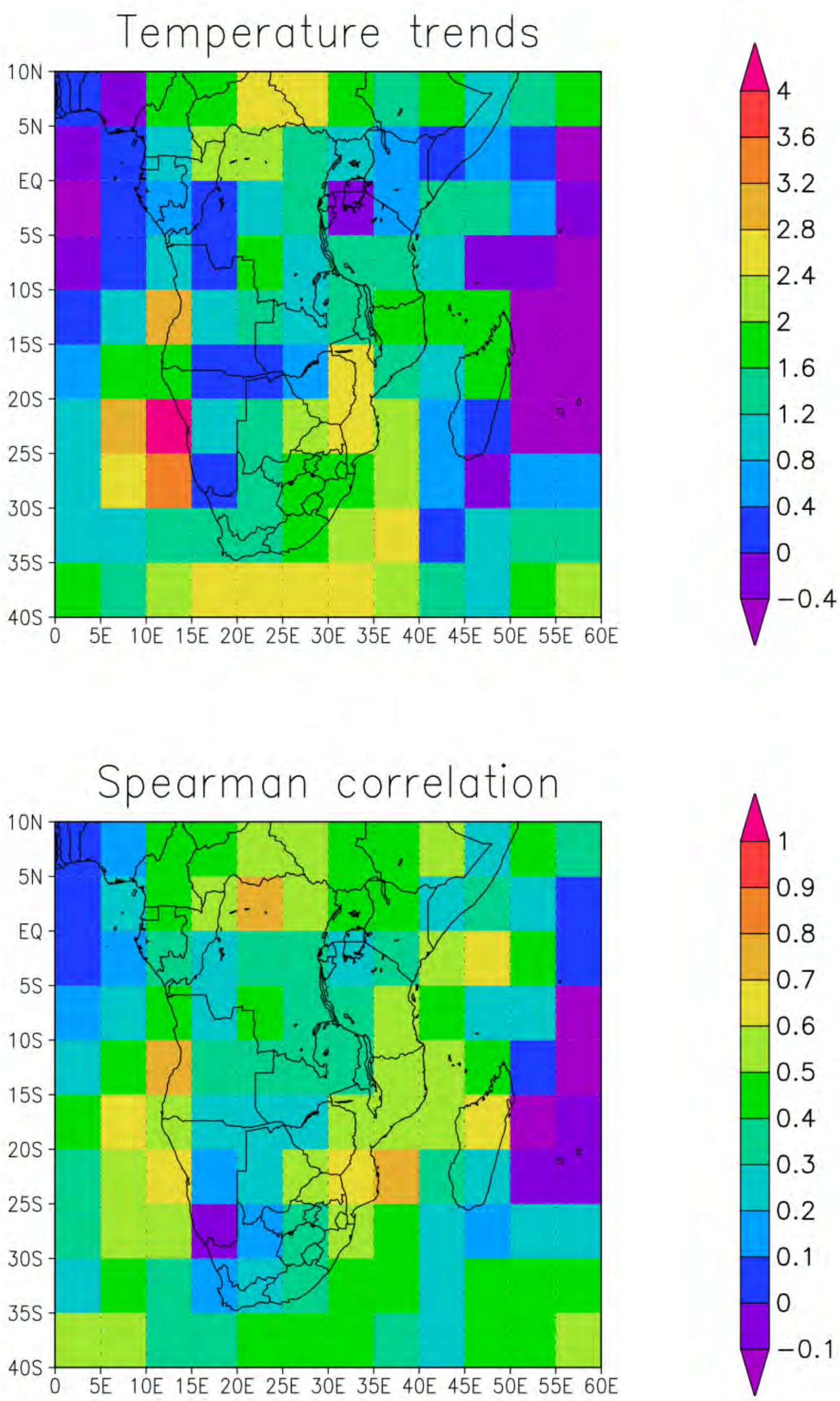

Figure 3.2: CCAM simulated temperature trends over southern Africa from the control experiment (top panel, units: °C/century) for the period 1979-2005. The associated Spearman rank correlations are shown in the lower panel.

In fact, the simulated trends are stronger than their observed counterparts, particularly over the eastern parts of South Africa. The Spearman rank correlations of the simulated trends are also relatively high, indicating that the simulated trends are statistically significant in general. Clearly, the AMIP-style simulations that incorporate the effects of CO_2 forcing produce very different (and in fact more realistic) trends in the simulated average annual temperatures, compared to the trends produced in the control experiment.

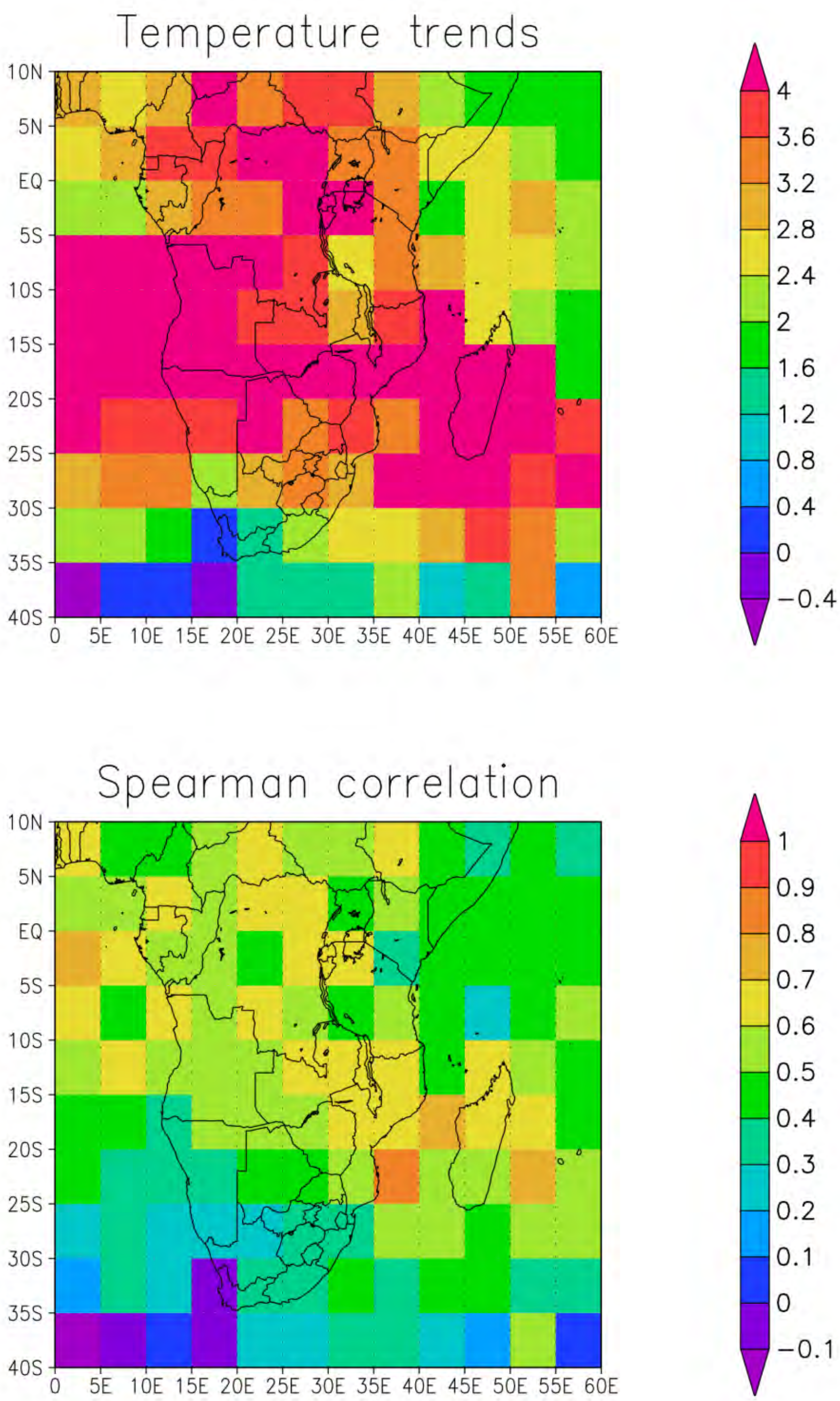

Figure 3.3: CCAM simulated temperature trends over southern Africa (top panel, units: °C/century) for the period 1979-2004 from experiment with realistically-varying greenhouse gas and ozone concentrations (experiment RFE1). The associated Spearman rank correlations are shown in the lower panel.

3. Experimental design – projections of future climate change over southern Africa

Regional climate modelling is used to downscale the projections of CMIP5 GCMs to high resolution over southern Africa for different mitigation scenarios, to explore the net impact of the enhanced greenhouse effect and recovering stratospheric ozone on southern African climate. The regional climate model used, CCAM, is a variable-resolution GCM developed by the CSIRO (McGregor 2005b; McGregor and Dix 2001, 2008). See Chapter 2 section 2, for a more complete description of CCAM. Here CCAM ran coupled to a dynamic land-surface model CABLE (CSIRO Atmosphere Biosphere Land Exchange model). A number of GCM simulations of CMIP5 and AR5 of the IPCC, obtained for the emission scenarios described by Representative Concentration Pathways 4.5 and 8.5 (RCP4.5 and 8.5) were downscaled to 50 km resolution globally. The simulations span the period 1971-2100. RCP4.5 is a high mitigation scenario, whilst RCP8.5 is a low mitigation scenario. The GCMs downscaled include the Australian Community Climate and Earth System Simulator (ACCESS1-0); the Geophysical Fluid Dynamics Laboratory Coupled Model (GFDL-CM3); the National Centre for Meteorological Research Coupled Global Climate Model, version 5 (CNRM-CM5); the Max Planck Institute Coupled Earth System Model (MPI-ESM-LR); the Model for Interdisciplinary Research on Climate (MIROC4h); the Norwegian Earth System Model (NorESM1-M); the Community Climate System Model (CCSM4); the Meteorological Research Institute Global Climate Model (MRI-GCM3); and the Institute Piere Simon Laplace Climate Modelling Centre Coupled Model (IPSL-CM5A-MR). The simulations were performed on supercomputers of the CSIRO (Katzfey et al., 2012) and on the Centre for High Performance Computing (CHPC) of the Meraka Institute of the CSIR in South Africa.

Results from the downscaling of these CGCMs are presented here. CCAM was forced with the bias-corrected daily sea-surface temperatures (SSTs) and sea-ice concentrations of each host model, and with CO_2, aerosol emissions and ozone forcing consistent with the RCP4.5 and 8.5 scenarios. The model's ability to realistically simulate present-day southern African climate has been extensively demonstrated (e.g. Engelbrecht et al., 2009; Engelbrecht et al., 2011; Engelbrecht et al., 2013; Malherbe et al., 2013; Winsemius et al., 2014; Engelbrecht et al., 2015). Most current coupled GCMs do not employ flux corrections between atmosphere and ocean, which contributes to the existence of biases in their simulations of present-day SSTs – of typically more than 2 ºC along the West African coast. An important feature of the downscalings performed here is that the model was forced with the bias-corrected sea-surface temperatures (SSTs) and sea-ice fields of the GCMs. The bias is computed by subtracting for each month the Reynolds (1988) SST climatology (for 1971-2000) from the corresponding CGCM climatology. The bias-correction is applied consistently throughout the simulation. Through this procedure the climatology of the SSTs applied as lower boundary forcing is the same as that of the Reynolds SSTs. However, the intra-annual variability and climate-change signal of the CGCM SSTs are preserved (Katzfey et al., 2009).

4. Projected meridional displacements in the westerlies over the southern ocean under climate change and impacts on southern African climate

Figures 3.4 and 3.5 show the projected 1000 hPa wind anomalies for January and July, respectively, for the far-future (2071-2100) relative to present-day conditions. The figure is for a case where CCAM was forced at its lower boundary with the output of a CGCMs, under a low mitigation scenario. The results are indicative of a pronounced poleward displacement of the westerlies, even for the far-future where stratospheric ozone concentrations have recovered to pre-industrial concentrations. The poleward displacement of the westerlies during winter is the primary region for the projected decrease in winter rainfall over the southwestern Cape region of South Africa (e.g. Christensen et al., 2007; Engelbrecht et al., 2009). For summer, the poleward displacement of the westerlies implies relatively stronger easterlies, which may well be favourable for rainfall over the eastern interior of southern Africa (also see Chapter 5 and the following discussion). These results are indicative of the dominant effect of the enhanced greenhouse effect on future climate change over the Southern Ocean and southern Africa. Projections obtain for the high mitigation scenario are qualitatively similar, and also indicate a southward displacement of the Southern Hemisphere westerlies. That is, the enhanced greenhouse effect is projected to have a dominating effect on future displacements of the westerlies, even in the presence of recovering stratospheric ozone and for the case of relatively strong mitigation (e.g. RCP4.5).

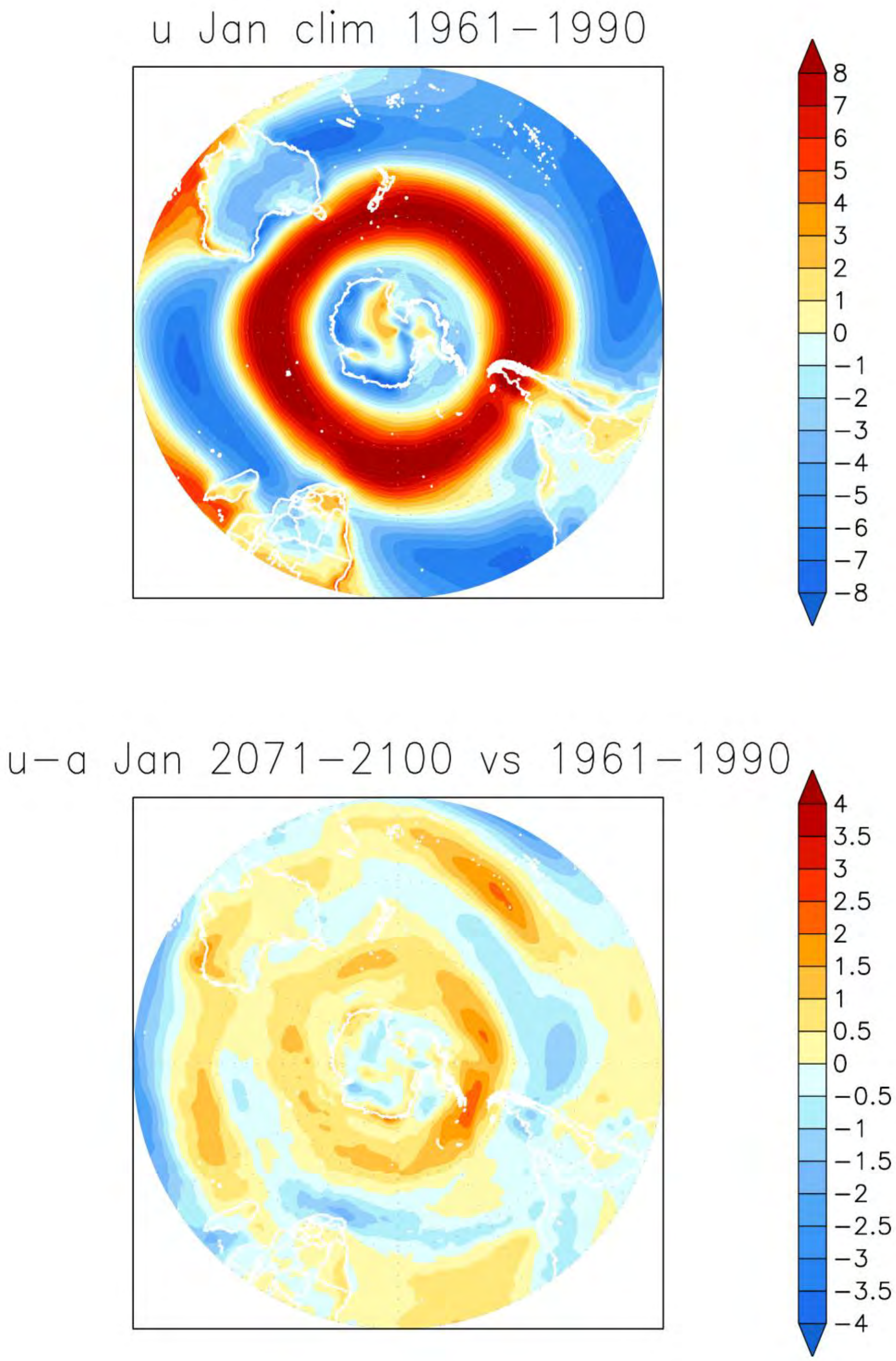

Figure 3.4: Model projected January 1000 hPa zonal wind anomalies for 2071-2100 relative to the present-day climatology, under a low-mitigation scenario of future greenhouse and stratospheric ozone concentrations.

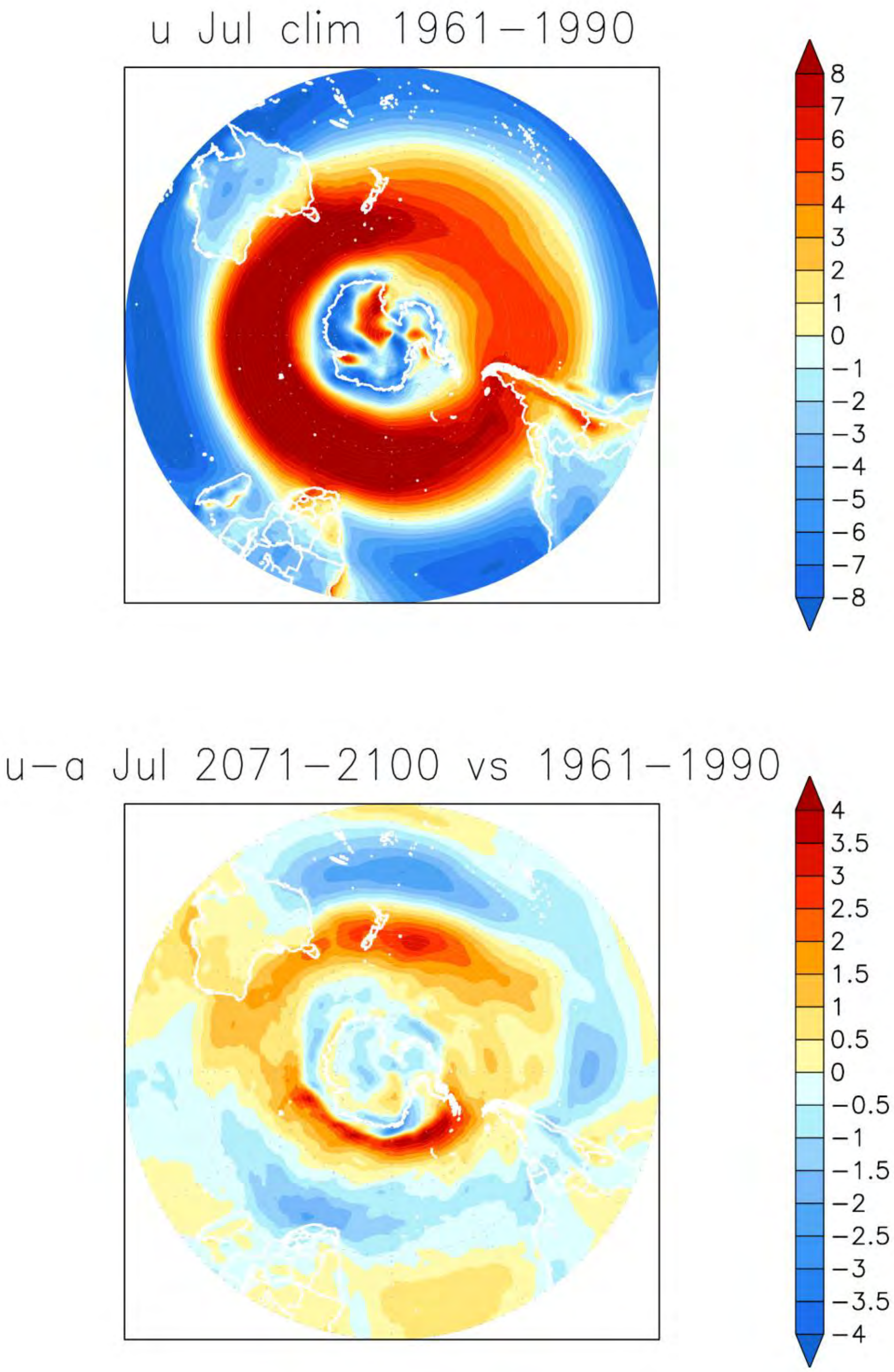

Figure 3.5. Model projected July 1000 hPa zonal wind anomalies for 2071-2100 relative to present-day climate, under a low mitigation emission scenario of future greenhouse and stratospheric ozone concentrations.

The range of CCAM-projected changes in average-annual temperatures and annual rainfall totals are displayed in Figs. 3.6 and 3.7, respectively, for the case of low mitigation, and for the period 2021-2050 relative to 1971-2000. The key results obtained may be summarised as follows:

Temperature

- Rapid rises in the annual-average near-surface temperatures are projected to occur over southern Africa during the 21st century – temperatures over the South African interior are

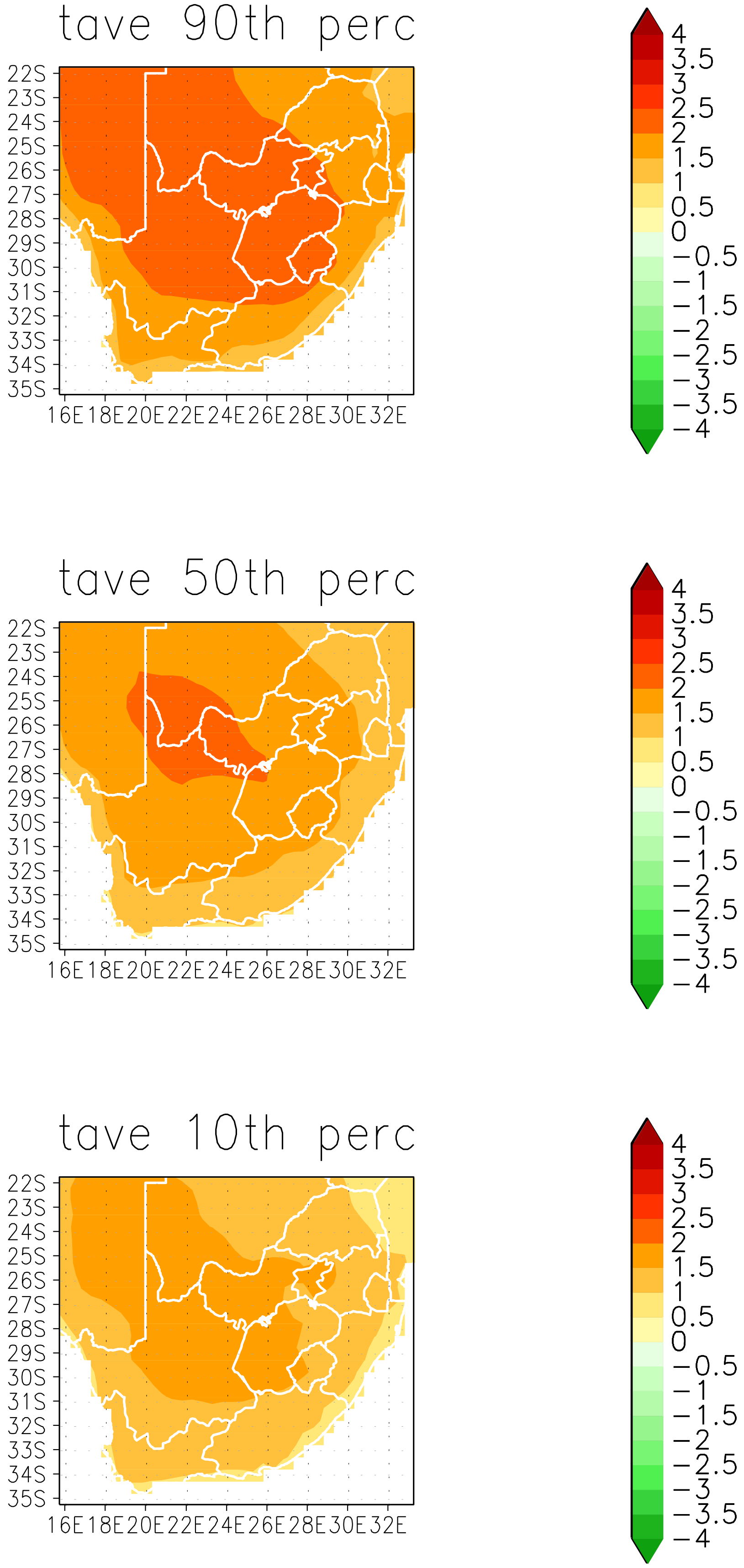

Figure 3.6: CCAM projected change in annual average temperatures (°C) over South Africa, for the time-slab 2021-2050 relative to 1971-2000. The 10th percentile (bottom), median (middle) and 90th percentile (top) are shown for the ensemble of downscalings of GCM projections under RCP8.5.

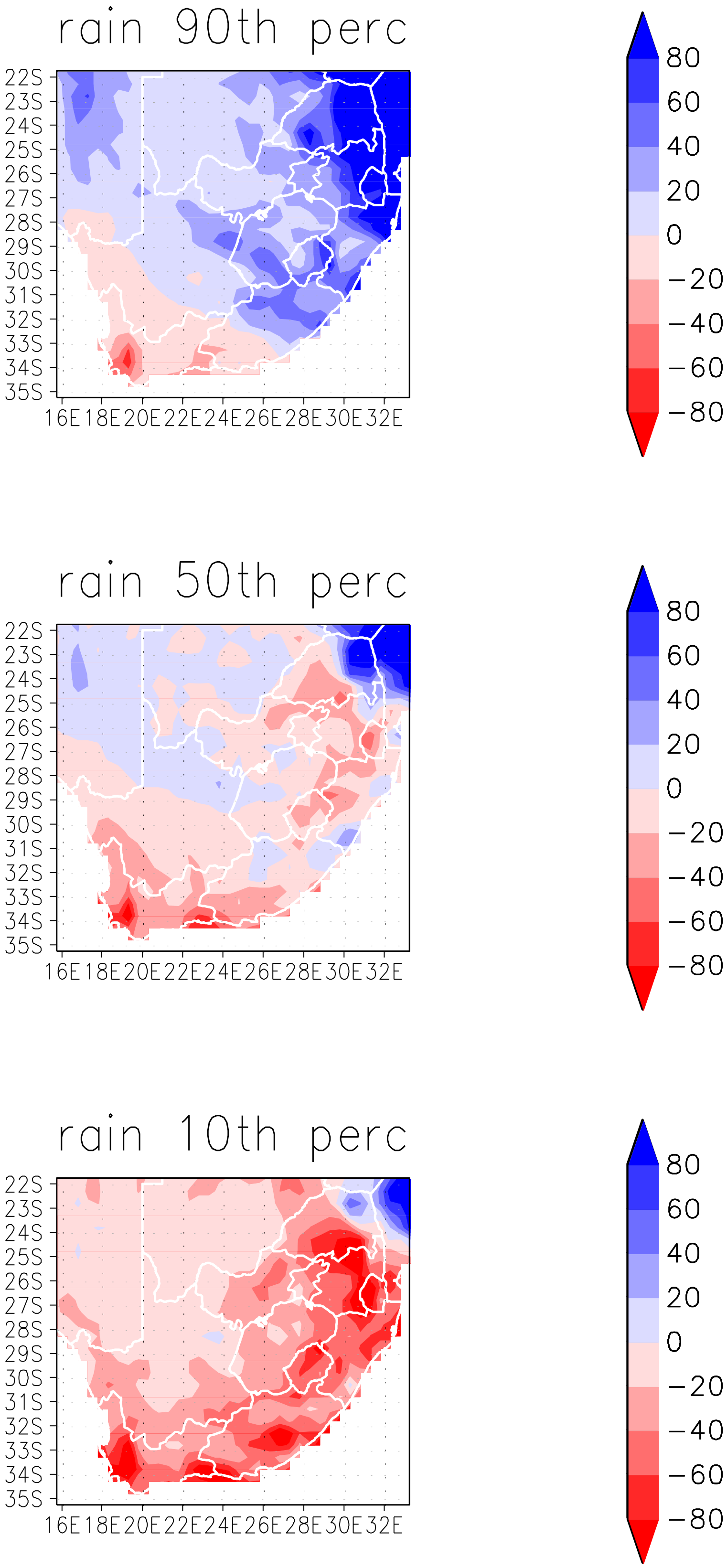

Figure 3.7: CCAM projected change in annual rainfall totals (mm) over South Africa, for the time-slab 2021-2050 relative to 1971-2000. The 10th percentile (bottom), median (middle) and 90th percentile (top) are shown for the ensemble of downscalings of six GCM projections under RCP8.5.

projected to rise at about twice the global rate of temperature increase (Engelbrecht et al., 2015).

• For the period 2021-2050 relative to the period 1971-2000, temperature increases of 1 to 2.5°C are projected to occur over the South Africa under low mitigation (Figs. 3.6a to 3.6c).

• Under high mitigation, temperature increases over South Africa will be somewhat less, although it may still reach 2.5°C over the central interior (not shown).

• Increasing average temperatures over South Africa may plausibly increase evaporation and evapotranspiration, with impacts for water security.

• By the end of the century, temperature increases of 4 to 7°C are projected to occur over the southern African interior under the RCP8.5 scenario. Such drastic temperature increases would have significant impacts on numerous sectors, including agriculture, water and energy.

Rainfall

• A general decrease in rainfall is plausible over southern Africa under enhanced anthropogenic forcing (e.g. Christensen et al., 2007; Engelbrecht et al., 2009).

• For the period 2021-2050 relative to the period 1961-1990, under low mitigation, rainfall is projected to decrease over South Africa in general and particularly over the southwestern Cape by most ensemble members (Figure 3.7a to 3.7c). Most ensemble members simultaneously project increases in rainfall over the central interior and the northeastern parts of Limpopo. A minority of ensemble members project general rainfall increases over eastern South Africa (Figure 3.7c).

• The projected changes in rainfall patterns under high mitigation (not shown) are very similar to the patterns projected under low mitigation.

• The projected changes in rainfall patterns over South Africa in the ensemble of downscalings described here, and more generally in the CGCM projections of AR4 and AR5, display more uncertainty than in the case of projected changes in temperature. This implies that adaptation policy makers need to take into account a range of different rainfall futures, often of different signal (i.e. drier and wetter) during the decision making process. The current body of evidence points strongly, however, to decreases in rainfall being likely over the winter rainfall region of the southwestern Cape and plausible over most of the South African interior.

5. Summary

The analysis of simulated temperature trends for the various radiative forcing simulations has yielded an important result – the inclusion of time varying CO_2 concentrations is essential to realistically simulate the observed trends, even in the presence of observed SST forcing. This result suggests that the local increased absorption of infra-red radiation through enhanced levels of CO_2 plays an important role in the strong temperature trends observed over southern Africa. Under low mitigation, and even under relatively high mitigation scenarios such as RCP4.5, the poleward displacement of the westerlies is projected to strengthen during the 21st century – despite the recovery of stratospheric ozone concentrations. This large-scale hemispheric change in the circulation is contributing to the projected changes of rapidly rising surface temperatures over southern Africa, and the robust projections of decreasing rainfall over the southwestern Cape. The maintained poleward displacement of the westerlies may also contribute to the occurrence of increased rainfall totals projected by some climate models over eastern South Africa, particularly during summer. Two PhD students are taking further the research described in this Chapter. Isaac Ngwana is exploring the effects of enhanced anthropogenic forcing on short-range predictability over southern Africa, whilst Mavhungu Muthige is exploring the impacts of enhanced anthropogenic forcing on tropical cyclone tracks over the southwestern Indian Ocean.

Chapter 4
Hemispheric dynamics of stratospheric ozone forcing and implications for southern African climate variability and change

1. Introduction

The radiative forcing sensitivity tests of Chapter 2 and the climate-change projections of Chapter 3 have provided strong evidence that forcing from anomalous stratospheric concentrations has an effect on Southern Hemispheric circulation patterns, with an associated impact on southern African climate – particularly in summer. The purpose of this chapter is to investigate in some detail the dynamics of this forcing mechanism, and to demonstrate from a dynamic-circulation perspective the functioning of this remote teleconnection to the subtropics of southern Africa. The experiment selected for the analysis is RFE2, in which time-varying stratospheric ozone was used as a radiative forcing in the 18-level model. The equivalent 27-level simulation (RFE7) produced qualitatively similar results.

2. Stratospheric and tropospheric mean state and variability

As the sun migrates to the Northern Hemisphere from the austral autumn through winter, it leaves

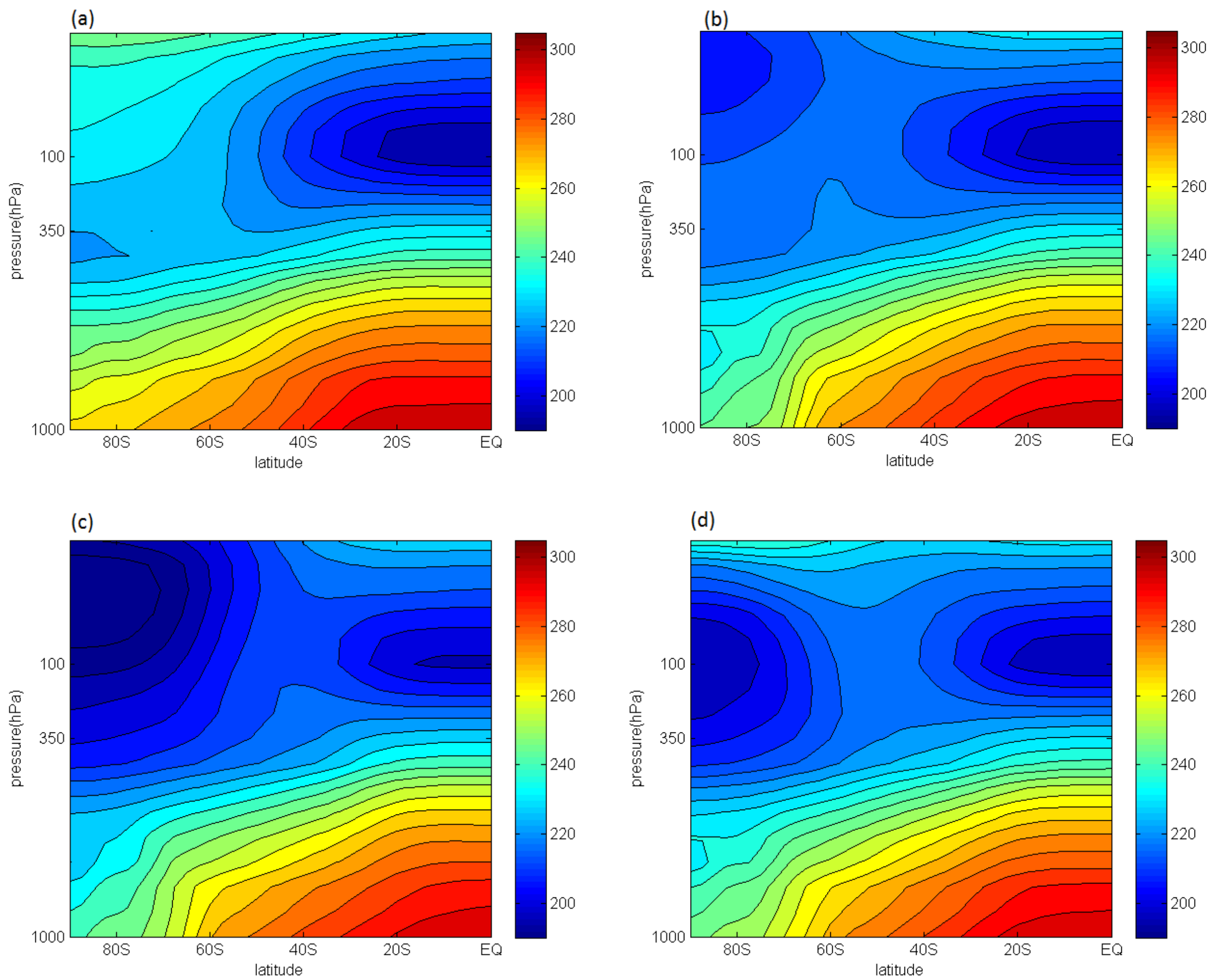

Figure 4.1: Climatological NCEP reanalysis zonally-averaged temperatures for the Southern Hemisphere mid-season months of (a) January, (b) April, (c) July and (d) October.

behind a cold South Pole. As a result, a strong equatorward meridional temperature gradient forms in the lower stratosphere (see Fig. 2 of Waugh and Polvani, 2010). The observed (as approximated by reanalysis data) and zonally-averaged temperatures for the Southern Hemisphere mid-season months are shown in Fig. 4.1. This process is simulated successfully by the CCAM radiative forcing experiments with time-varying ozone (RFE2 and RFE7, see Table 1), in which the ozone forcing is time-varying as in the real atmosphere (described by observed time-varying ozone forcings) (Fig. 4.2). An important difference between the reanalysis and simulations, is that the model polar stratosphere is somewhat colder than in the observations. This is noted right through the year, including during the summer months (compare Figs. 4.1a for the case of NCEP reanalysis, and 4.2a for the case of the CCAM simulations). This gives rise to a relatively weak lower-stratospheric meridional temperature gradient in CCAM RFE2.

By the thermal wind relation, a strong vertical shear in the stratosphere appears from autumn to spring, as a result of the lower-stratospheric meridional temperature gradient. This reverses the stratospheric flow, from being easterly during the summer to westerly from about March, as shown in Fig. 4.3a, and polar vortex forms as a result. The polar night jet that forms allows large-scale Rossby waves to propagate vertically upwards into the winter stratosphere. By the Charney-Drazin criterion (Charney and Drazin, 1961), this vertical propagation only takes place in weak westerly zonal flow. This results in a more perturbed boreal winter hemisphere.

The relative strength of the polar vortex between hemispheres in both datasets (NCEP reanalysis and CCAM simulations) is similar (compare Figs. 4.3a and 4.3b). That is, in both NCEP reanalysis and CCAM experiment RFE2, the polar night jet is much stronger during the austral winter than during the boreal winter. This is a well-established result (e.g. Waugh and Polvani, 2010) that CCAM is clearly able to simulate. The reason for this is that the Northern Hemisphere is characterised by large topographical features, such as the Himalaya and the Rocky Mountains, as well as large temperature gradients between land and sea. This gives rise to planetary scale (wavenumber 1, 2 and 3) standing Rossby waves that propagate in three dimensions and, in particular, vertically into the stratosphere. These waves perturb the NH stratospheric flow, through wave-mean flow interaction mechanisms (Andrews et al., 1987). Large scale standing waves also exist in the SH (van Loon and Jenne,1972), but not to the same extent, of course, because most of the SH is covered by water and there are no topographical features that are as large as the Himalayas and Rockies. Consistently, the Southern Hemisphere stratospheric flow is stronger. Most large-scale waves that occur in the SH are transient and may be stimulated by baroclinic disturbances in the troposphere, rather than topography as it is the case with their boreal standing counter parts. Note that that transient large scale waves do occur in the NH, but just not to the same extent as standing waves.

The 0 m/s isotachs in Figs. 4.3a and 4.3b indicate that the reversal of the zonal flow does not occur entirely in the CCAM experiment RFE2. It may be concluded that this is a result of the related weak lower stratospheric meridional temperature gradient that is persistent right through the summer months in the model simulations. Furthermore, the polar vortex is stronger in the CCAM simulation (compare Figs. 4.3a and 4.3b). The model South Pole is also colder than in the NCEP reanalysis. Again, this is consistent with the thermal structure in the CCAM experiment RFE2. It has therefore been established that the polar vortex in CCAM's Southern Hemisphere does not completely break. This deficiency in the model simulations might have implications for the simulation of stratosphere-troposphere coupling – an aspect that will be discussed in more detail in the next section.

The thermal structure of the lower troposphere plays a crucial role in the seasonal changes that are observed in the mid-latitudes. The meridional temperature gradient (Figs. 4.4a and 4.4b) in the lower troposphere causes the presence of the eddy-driven jet that is found in the mid-latitudes (Figs. 4.4c and 4.4d). The jet is driven by eddies, in that momentum that is first transported poleward by the Hadley circulation, is transported further south by the eddies from the latitude where the descending component of the Hadley cell is located. The eddies then affect poleward fluxes and deposit the momentum into the jet to accelerate it, via the divergence of these fluxes (see Kim and Lee, 2004). Synoptic-scale Rossby waves have to break for this to occur efficiently because of the north-west/south-east slant of the trough axis associated with this process (Postel

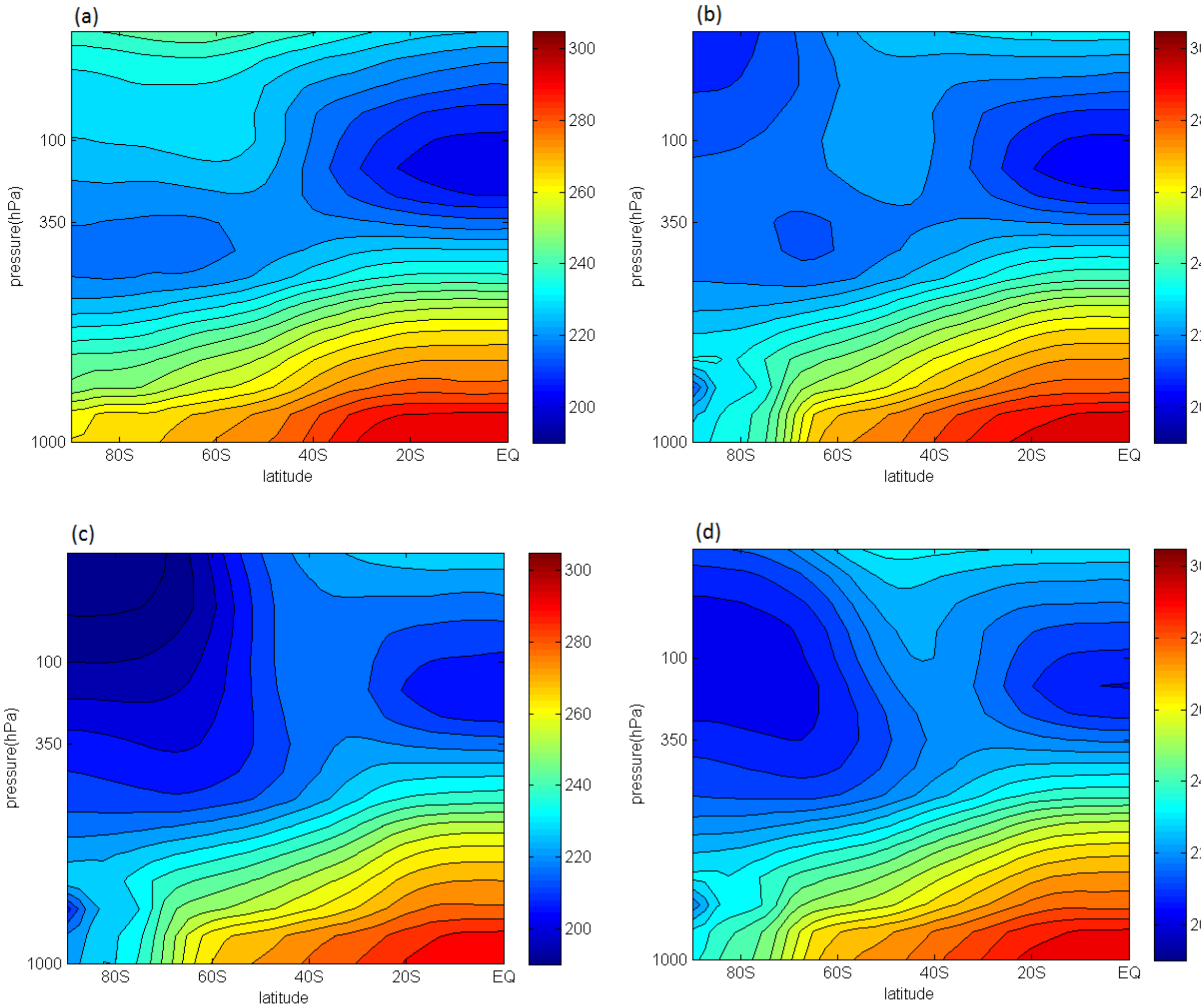

Figure 4.2: Same as Figure 4.1, but for CCAM RFE2 (see Table 1).

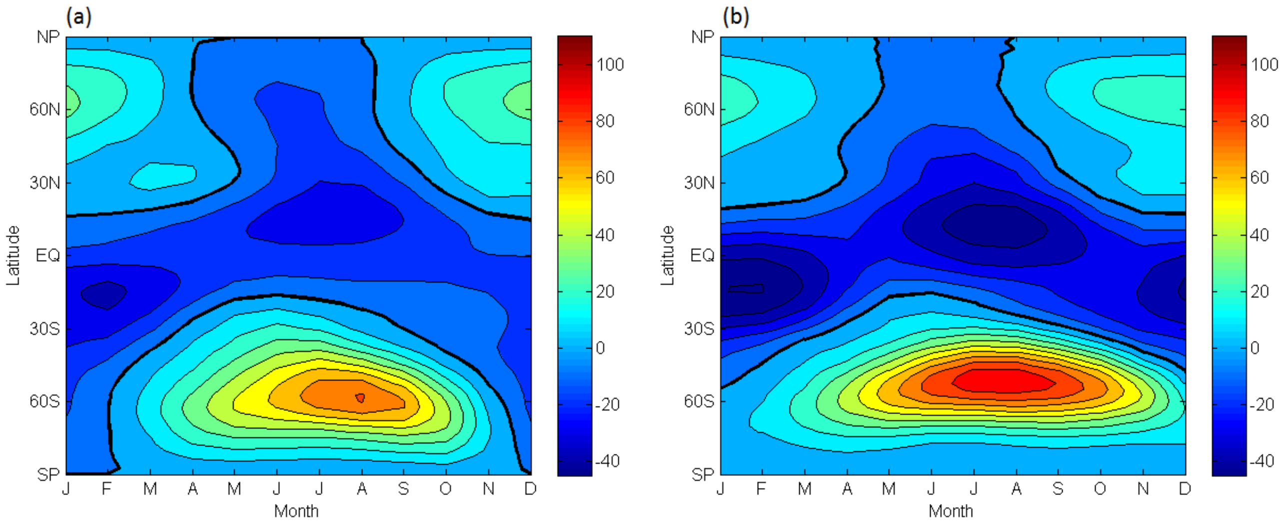

Figure 4.3: Zonally averaged winds at the 10 hPa levels for (a) NCEP reanalysis data and (b) CCAM simulation in which lower stratospheric ozone concentrations vary in space and time according to observations (RFE2). The thick black contour represents the 0 m/s isotach.

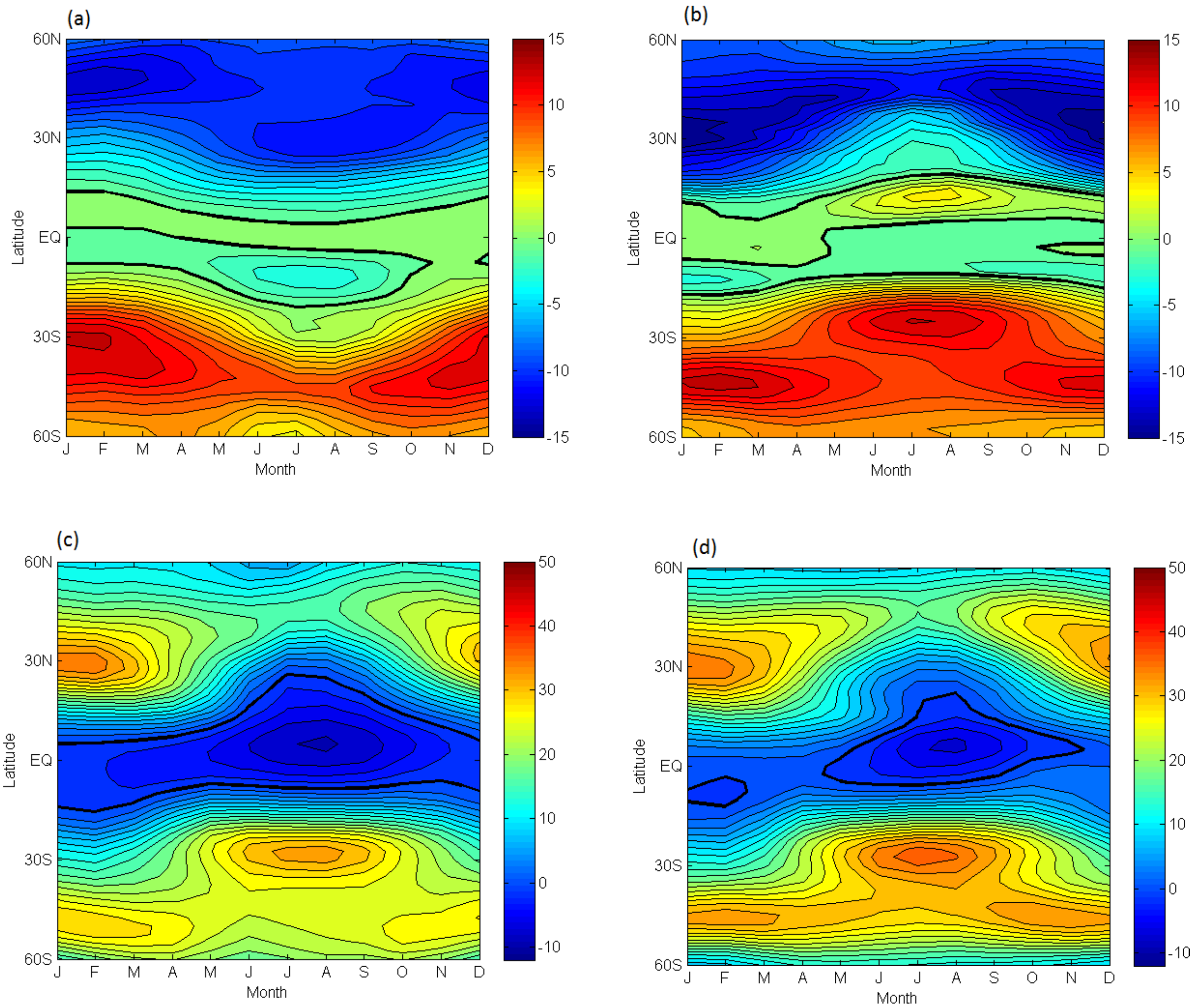

Figure 4.4: Contour plot of the meridional temperature gradient (units are $10^8 Km^{-1}$) at 700 hPa (top panels) and zonally winds (ms^{-1}) at 300 hPa (bottom panels) for (a, c) NCEP reanalysis and (b,d) CCAM. Both fields are plotted as a function of month.

and Hitchman, 1999). As the momentum is transported by the eddies, it also acts to convert eddy kinetic energy to mean kinetic energy, that is, it acts to increase the kinetic energy of the jet stream (Holton, 2004). During the winter months the thermally driven subtropical jet develops in both datasets (NCEP reanalysis and the CCAM simulations).

3. The impact of ozone depletion on the tropospheric circulation

Studies that investigate the climatological effects of ozone depletion typically commence by considering the variability of the stratospheric southern polar-cap (70S-90S) temperatures as shown in Fig. 4.5, because the immediate impact of this forcing is first and foremost seen in these fields, and then thereafter in the tropospheric response that follows. Fig. 4.5 compares the seasonal evolution of polar-cap temperatures for the case of the control experiment performed in Chapter 2, to the corresponding fields of RFE2 (a simulation performed with time-varying stratospheric ozone concentrations). Both the control and RFE2 experiments exhibit a cold polar-cap during the winter months, which persists into spring. This is largely due to the sun having migrated to Northern Hemispheric summer. Whilst the control polar stratosphere is colder than its RFE2 experiment counterpart in the middle of the winter, the former is colder during the spring. This is, of course, consistent with what we expect to find as a result of time varying ozone in the RFE2 experiment (that is, in the RFE2 experiment stratospheric ozone concentrations are depleting over time as observed, with an associated cooling effect on spring temperatures).

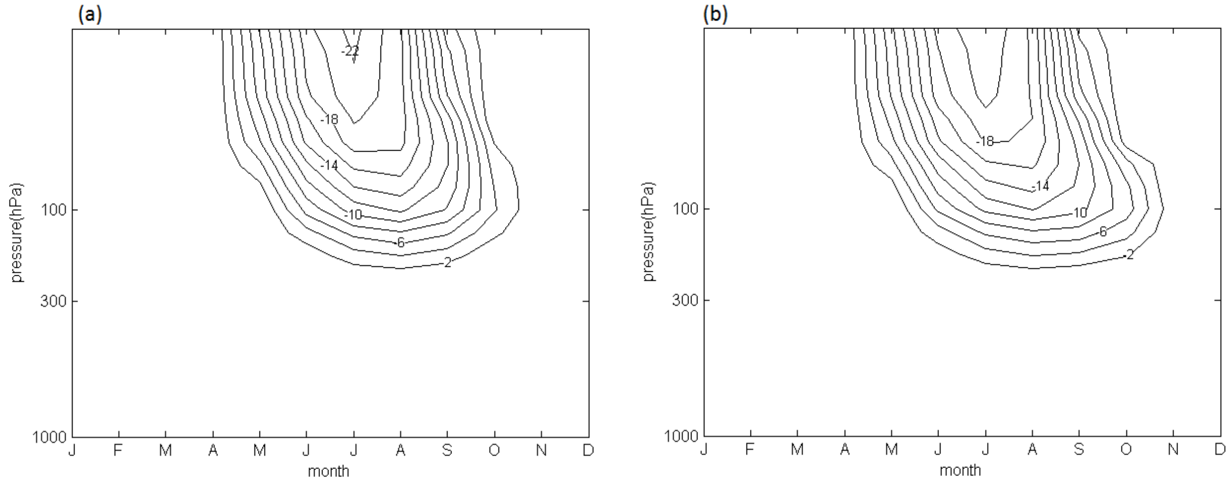

Figure 4.5: The evolution of polar-cap (70S-90S) temperatures as a function of month for (a) the control and (b) the RFE2 experiment with time-varying ozone forcing. These temperature fields are represented as temperature – 200K, following Randel and Newman (1999).

Whilst the climatological evolution of polar-cap temperatures are similar between experiments as just outlined, in contrast, temperatures trends are very different. The control-experiment temperature exhibits very little change in lower stratospheric temperatures during the spring months as the polar vortex breaks up (see Fig. 4.6a). This is due to the fact this simulation is forced with climatological values of radiative forcing, and in particular with climatological stratospheric ozone forcing. This means that in the control experiment there is no ozone depletion taking place. When ozone concentrations are varied according to observations, the well-known stratospheric cooling result (see Figure 4.6b) that has been obtained in other modelling studies (e.g. Son et al., 2010) appears here as well.

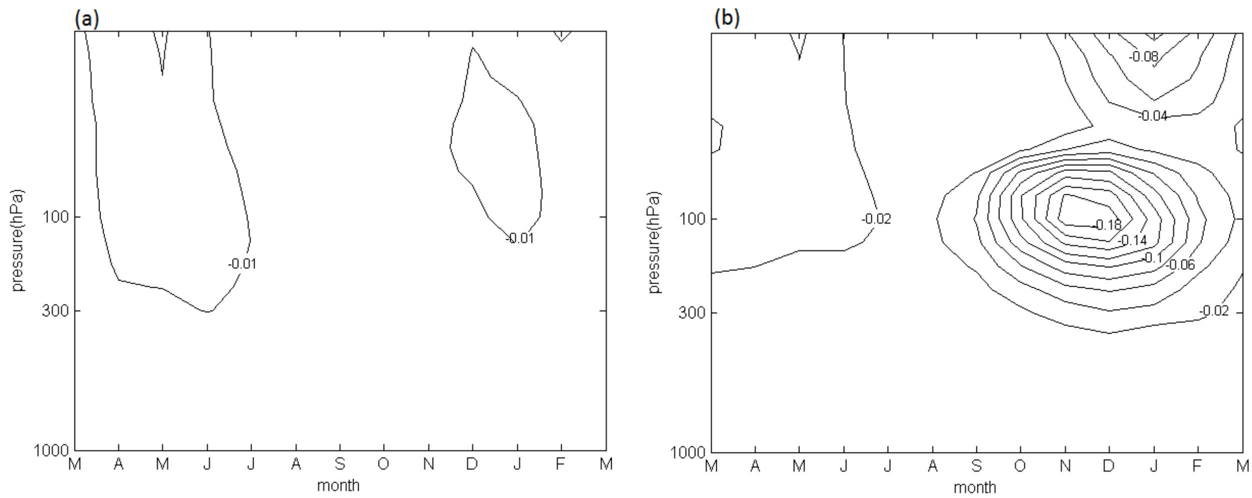

Figure 4.6: Same as in Figure 4.5 but for temperature trends (units are °C/year).

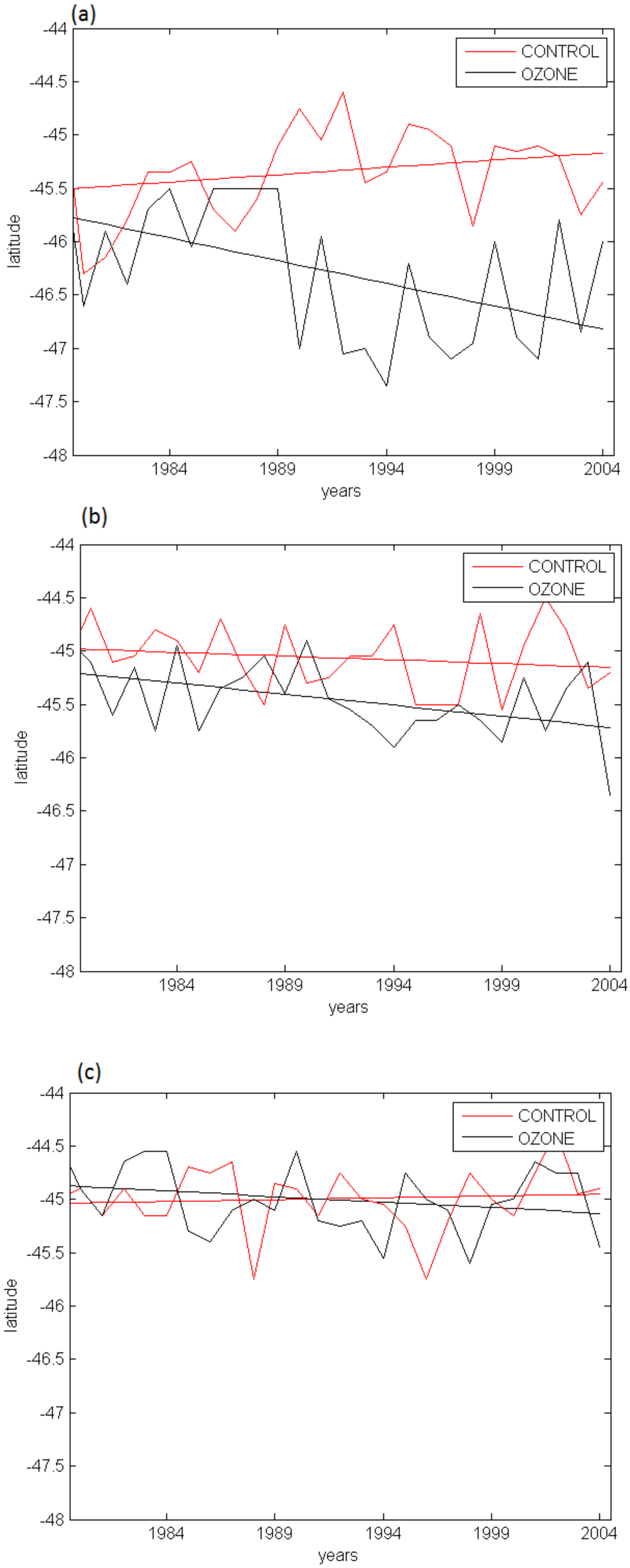

Figure 4.7. The variability of the latitudinal location of the jet and its trend for (a) December, (b) January and (c) February. The red and black lines are for the control and RFE2 experiments, respectively.

The CCAM-simulated stratospheric cooling appears in spring and continues right through into the summer months, closely corresponding to how it has been simulated by models with interactive stratospheric chemistry (e.g. Waugh et al., 2009), and as it has been observed (Thomson and Solomon, 2002). The well-known response to this cooling is a movement of the eddy-driven jet during the summer toward the poles, and this indeed occurs in the CCAM simulations. This is most clearly seen for December, as shown in Fig. 4.7 as compared to the other months. Fig. 4.7 also shows that the jet in the control experiment does not undergo a poleward migration as its RFE2 counterpart – indicating the importance of including stratospheric ozone forcing in order to realistically simulate Southern Hemisphere climate variability and change.

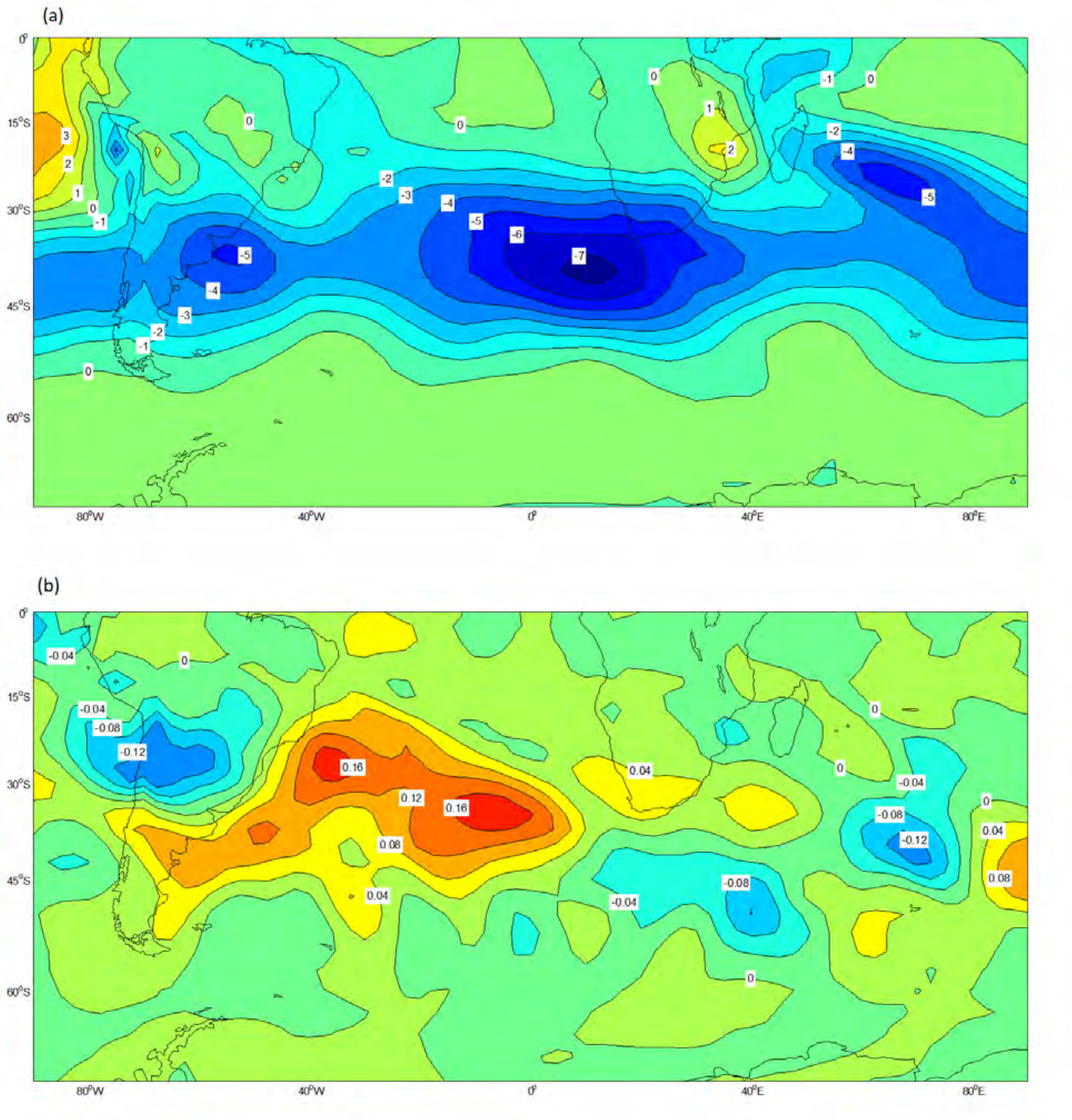

Figure 4.8: (a) Eddy momentum fluxes (m^2s^{-2}) and (b) associated trends ($m^2s^{-2}year^{-1}$) for the control experiment for December.

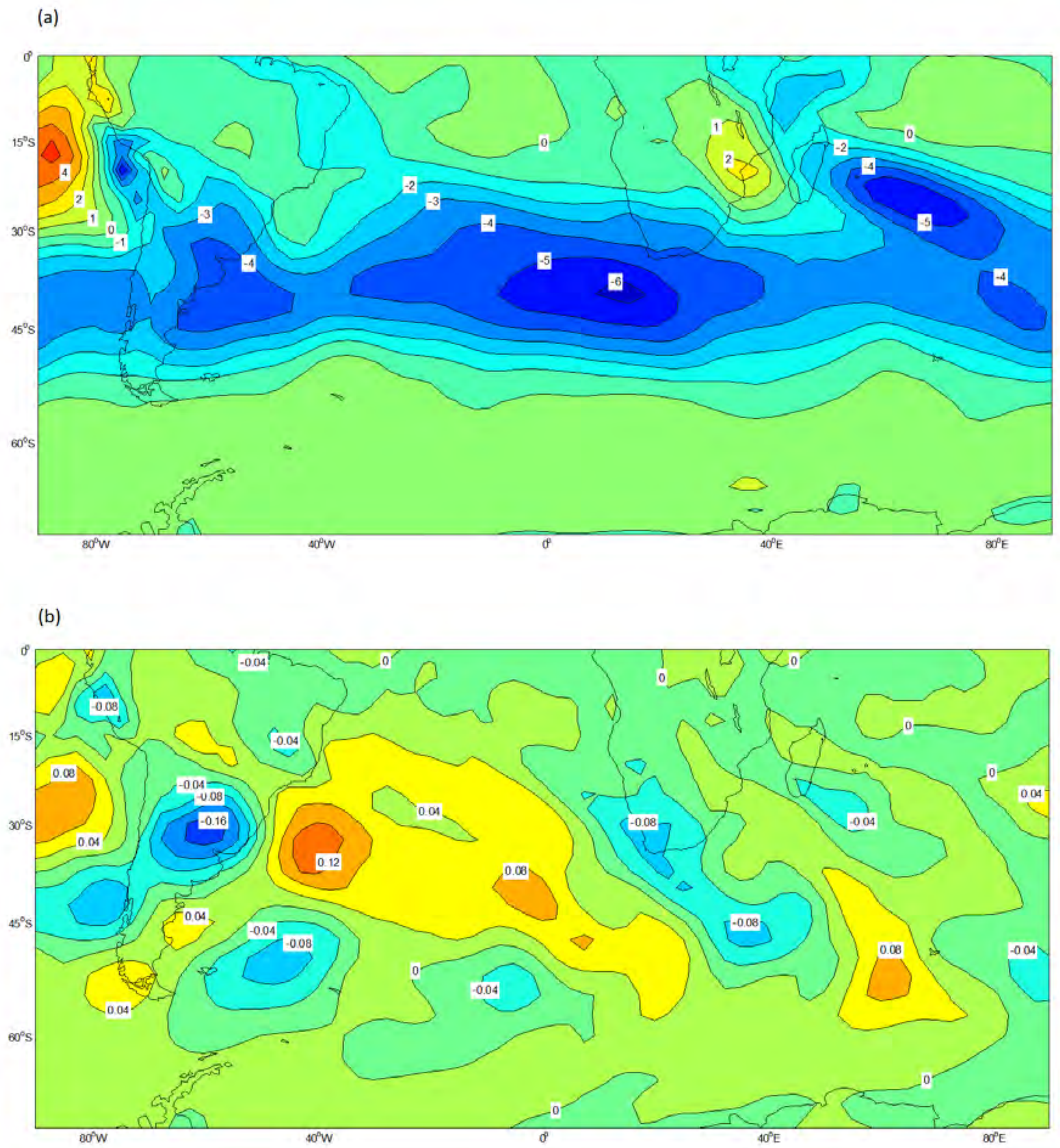

Figure 4.9: Same as in Fig. 4.8, but for the RFE2 experiment.

To develop an appreciation of what these changes imply for the South African climate system, we consider eddy momentum fluxes. We only show these for December, because of the pronounced poleward shift of the jet stream that have been observed and simulated to occur during this month (Fig. 4.7a). Here the basic state flow is time-symmetric to allow for the zonal variations to show. Poleward eddy momentum fluxes play a crucial role in the conservation of angular momentum and energy in the subtropics and mid-latitudes. These fluxes deposit angular momentum into the jet and convert eddy kinetic energy to mean kinetic energy, which then accelerates the mid-latitude jet. The poleward momentum fluxes are facilitated by highly developed weather systems, which essentially occur at the end of baroclinic life-cycles (Thorncroft et al., 1993), as the trough axis in low pressure systems tilts westward. Figs. 4.8b and 4.9b suggest that the impact of ozone depletion is a reduction in the frequency of weather systems that mature in the South Atlantic, just off the west coast of South Africa. The negative trends over the country suggest that some of these weather systems mature over the western parts of the country as a result of ozone depletion, whereas if no ozone depletion occurs they move south of the country. This has potentially huge implications for South Africa. In fact from the above, it can be hypothesized that ozone depletion could have caused an increase in summer rainfall in the summer rainfall region of South Africa.

There is evidence of such a change from climate model simulations (e.g. Engelbrecht et al., 2009; also see Chapter 3) and observations (e.g. Kruger, 2006). Moreover, the analysis presented here provide insight in the improved skill of the AMIP-style simulations RFE2 and RFE7 (which take into account time-varying radiative forcing) in simulating the inter-annual variability of summer rainfall over South Africa (compared to the control simulation).

4. Summary

CCAM's RFE2 simulation is able to reproduce the most important dynamic and thermodynamic features of the stratosphere and the troposphere. The most important shortcoming in the simulations is the colder South Pole (compared to observations) and a persistent relatively weak meridional temperature gradient in the stratosphere, particularly for the summer months. This systematic error prevents the full reversal of the stratospheric flow to occur in the model simulations. This might have implications for the simulation of stratosphere-troposphere coupling. The tropospheric circulation is simulated realistically in general.

Forcing CCAM with time-varying ozone fields enables the model to successfully simulate the impact of ozone depletion. All the well-known results from studies that have been conducted with chemistry-climate models with interactive stratospheric chemistry have been reproduced here, including the pronounced poleward displacement of the Southern Hemisphere westerlies under stratospheric ozone depletion. Momentum fluxes demonstrate the impact that ozone depletion may have had on weather systems affecting South Africa. It appears to have shifted some of the weather systems eastward and southward, with enhanced easterly flow over South Africa in summer. Such a change may have played a role in causing increasing trends in rainfall over eastern South Africa in summer (e.g. Kruger, 2006).

Chapter 5
Conclusions

The project was successful in performing a large set of radiative forcing experiments, aimed mainly at describing the radiative forcing effects of Antarctic stratospheric ozone, increasing CO_2 concentrations and time-varying aerosol forcings on dynamic circulation variability over the Southern Ocean and southern Africa. An ensemble of projections of future climate change has also been analysed, to investigate the relative importance of enhanced CO_2 concentrations and recovering stratospheric ozone in forcing southern African climate during the 21st century. A number of conclusions can be drawn from the research:

- The simulations of seasonal circulation anomalies are most skilful for the austral summer in the control experiment. This result provides some insight into the relatively high levels of skill reported in general for the prediction of summer rainfall totals over southern Africa at the seasonal time-scale (compared to other seasons) (e.g. Mason et al., 1996, Landman and Mason, 1999; Landman et al., 2005; Landman et al., 2009). Clearly, this skill stems from the underlying circulation fields being forecasted more skilfully for summer. The drastic reduction in skill that occurs in the autumn, winter and spring seasons over southern Africa may attributed at least partially to the northward-displaced westerlies with its transient weather systems, of which the inter-annual variability is simulated less skilfully. Another important contributing factor may be that ENSO related SST anomalies are generally the largest during the early summer, with important regional SST anomalies such as those associated with the South Indian Ocean subtropical dipole being the largest in the late summer (Reason et al., 2000). That is, the abilities of the tropical Pacific Ocean and regional oceans to force climate variability over southern Africa are reduced outside the austral summer. The relatively low skill of the model in simulating the inter-annual variability in autumn, winter and spring circulation over southern Africa is an important finding of the project, as the postulated underlying reasons for this low skill imply that improvements in forecast skill for these seasons may be extremely difficult to attain (and should not be sought in the first place through parameterisations, e.g. convective rainfall parameterisations).

- The inclusion of time-varying stratospheric ozone concentrations improves the simulation skill of circulation variability over the Southern Ocean in spring, and over southern Africa in summer. This is perhaps the most significant finding of the radiative forcing experiments. The result is consistent with dynamic circulation theory, according to which stratospheric forcing over Antarctica in spring has a pronounced mid-latitude response in summer (e.g. Thompson and Solomon, 2002). However, this study is the first to demonstrate that this response actually reaches the subtropical latitudes of southern Africa.

- The inclusion of time-varying CO_2 concentrations offer some benefit to the simulation of summer-time inter-annual variability, particularly in the tropics. The simulated changes in skill are, however, negative for most other seasons and regions.

- The prognostic treatment of aerosols is problematic in the model simulations of winter-time inter-annual variability, and leads to decreases simulation skill over the southern African interior. However, the inclusion of time-varying aerosol forcing leads to improvements in simulating spring and summer inter-annual variability over large parts of the African continent.

- The analysis of simulated temperature trends for the various radiative forcing simulations has yielded an important result – the inclusion of time-varying CO_2 concentrations is essential to realistically simulate the observed trends, even in the presence of observed SST forcing. This result suggests that the local increased absorption of infra-red radiation through enhanced levels of CO_2 plays an important role in the strong temperature trends observed over southern Africa.

- Under low mitigation, and even under relatively high mitigation scenarios such as RCP4.5, the poleward displacement of the westerlies is projected to strengthen during the 21st century – despite the recovery of stratospheric ozone concentrations. This large-scale hemispheric change in the circulation is contributing to the projected changes of rapidly rising surface temperatures over southern Africa during winter, and the robust projections of decreasing rainfall over the southwestern Cape. The maintained poleward displacement of the westerlies may also contribute to the occurrence of increased rainfall totals projected by some climate models over eastern South Africa, particularly during summer.

- The CCAM simulations forced with time-varying ozone concentrations are able to reproduce the most important dynamic and thermodynamic features of the stratosphere and the troposphere. The most important shortcoming in the simulations is the colder South Pole (compared to observations) and a persistent relatively weak meridional temperature gradient in the stratosphere, particularly for the summer months. This systematic error prevents the full reversal of the stratospheric flow to occur. This might have implications for the simulation of stratosphere-troposphere coupling. The tropospheric circulation is simulated realistically in general.

- Forcing CCAM with time-varying ozone fields enables the model to successfully simulate the impacts of ozone depletion. All the well-known results from studies that have been conducted with chemistry-climate models with interactive stratospheric chemistry have been reproduced in the CCAM simulations, including the pronounced poleward shift of the westerly winds in summer. Momentum fluxes demonstrate the impact that ozone depletion may have had on weather systems affecting South Africa. It appears to have shifted some of the weather systems eastward and southward, with enhanced easterly flow over South Africa in summer. This forcing effect may at least partially explain the existing evidence for observed increases in summer rainfall over parts of eastern South Africa (e.g. Kruger, 2006) and associated model projections of increasing rainfall totals over these regions under enhanced anthropogenic forcing (e.g. Engelbrecht et al., 2009; Engelbrecht et al., 2011).

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